

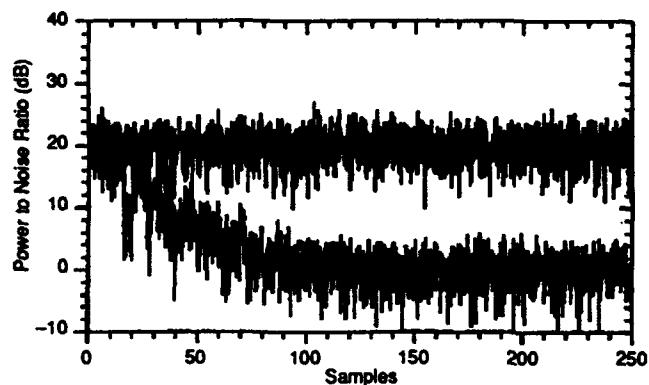
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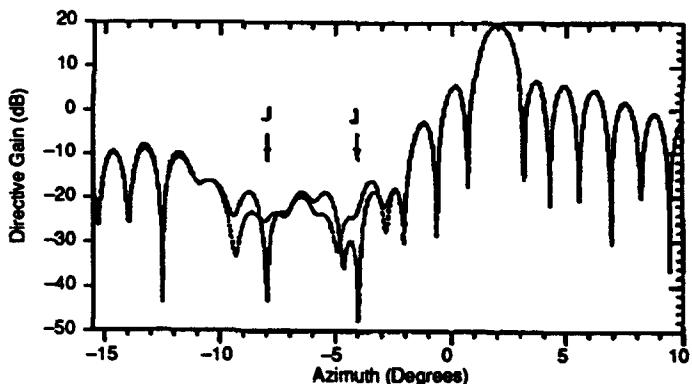


## Adaptive Processing Capability

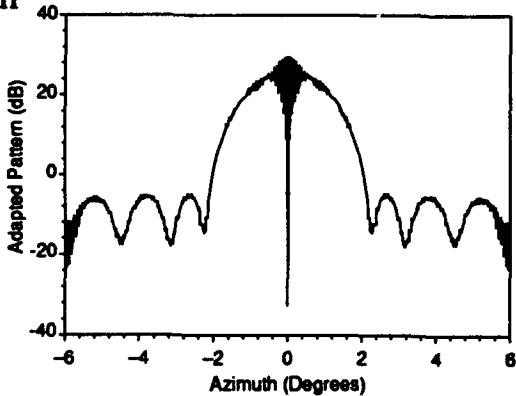
Interference Rejection in Time Domain



Sidelobe Cancellation



Mainlobe Cancellation



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## Section 1

### Adaptive Processing at MITRE

MITRE's engineering expertise in adaptive processing spans conceptual analysis, implementation, and test, and is rooted in system applications including airborne as well as surface-based sensor systems. This capability complements laboratory and university-based technology activity. MITRE's experience provides real-life system perspectives by exploiting related activity on other systems, as well as the unique capabilities of its personnel as outlined herein.

Adaptive processing provides a means for removing jamming and clutter interference from radar and communications systems. The interference could come from hostile or friendly forces. Adaptive processing will become an increasingly important element in radar, command and control, and communications systems in both peace and wartime environments. Consequently, The MITRE Corporation has committed itself to maintaining a leadership position in this important technology. It has devoted considerable internal research and development funds and has assembled a prestigious team of scientists and engineers to provide a capability which can be drawn upon by both defense and nondefense government agencies.

The MITRE Corporation is an independent, not-for-profit organization operating in the public interest that conducts research and provides systems engineering and acquisition support to U.S. Government agencies. An overview of the Corporation is provided in Section 2. The adaptive processing capability is a cross-corporate capability at MITRE. Resumés of staff members having special interest and expertise in

the field of adaptive processing are presented in Section 3. A listing of significant documentation relevant to adaptive processing is provided by author as part of the resumés.

The adaptive processor is characterized by its architectural configuration, as well as by the domain in which the nulling is performed. The cancellation can be performed in the angle, time, frequency, polarization, or signal space domains. Angle and polarization domain cancellers utilize auxiliary antennas to obtain samples of the interference. Cancellers in the other domains can be implemented after beamforming at the output of the antenna. Although the angle domain canceller is the most common, it can be combined with time and frequency domain processing to improve performance.

The samples of the interference obtained from auxiliary antennas in the angle domain canceller are multiplied by complex (amplitude and phase) weights and then recombined with the signals received through the main antenna to cancel the interference. The adaptive processor is characterized by its architectural configuration, as well as by the domain in which the nulling is performed. The auxiliary antennas, for example, can be part of, or separate from, the main antenna or array. The weights can be applied to individual elements (element space canceller), to subarray outputs (subarray space canceller), or even to the outputs of full beams (beamspace canceller).

Space Time Adaptive Processing (STAP) is currently one of the areas of significant interest. The technique is used primarily in pulse Doppler airborne

radars to remove sidelobe clutter. Implementation requires passing each of the auxiliary signals through a tapped delay line whose tap spacing is equal to the pulse repetition interval of the pulse Doppler waveform. MITRE has provided pioneering work in the area of STAP. The work has been supported by the Air Force and by internal R&D funds under the MITRE Sponsored Research (MSR) and Mission-Oriented Investigation and Experimentation (MOIE) programs. A paper documenting some of the results of this effort is reprinted in Section 4, *Performance of Space-Time Adaptive Airborne Radar*.

The MITRE Corporation has a long history of being a leader in the field of high frequency (HF) radar and communication. The Corporation has implemented an experimental HF array on land owned by the University of Texas near Odessa, Texas to test out new concepts and study phenomenology. One of the concepts tested is the possibility of cancelling background noise whether its origin be man-made or natural. To this end, MITRE has demonstrated the feasibility of cancelling background noise attributable to lightning. The investigation used digital data obtained from the elements in the Texas array. MITRE researchers also fabricated a sidelobe canceller to null out the interference in real time. A summary of the program is contained in two papers, *High Frequency Atmospheric Noise Mitigation* and *Wide-Bandwidth HF Noise Mitigation Using a Real-Time Adaptive Sidelobe Canceller* reprinted in Section 4.

Reduced-rank subspace projection methods are used indirectly in frequency and angle-of-arrival estimation algorithms, but are not commonly used in least-squares detection applications. MITRE has been exploring their use in processing underwater acoustic array data for detection and target localization. Several techniques have been developed

and applied to signals recorded from different types of arrays. This approach to adaptive beamforming employs principal component analysis of a narrowband array data matrix. The data matrix is decomposed into the sum of orthogonal matrix components, using singular value decomposition analysis. This analysis, like the usual eigenanalysis, allows partitioning of the acoustic field into spatially coherent "signal" and noncoherent "noise" subspaces. When such a partition is made, the estimated noise subspace can be discarded. Although a small amount of signal is also discarded, a significant improvement in signal-to-noise ratio can be realized. The methodology is discussed in more detail in the paper reprinted in Section 4, *A Principal Components Sidelobe Cancellation Algorithm*.

Under contract to the Army, MITRE has been investigating the problem of mainlobe cancellation. The problem is to cancel the jammer without cancelling the desired signal. When the jammer is within the antenna beamwidth, the width of the notch is so wide that there is a high probability that a desired target return will fall in the notch and be cancelled along with the jammer. One of the dominant issues is how close can the target return get to the jammer and still be detected. MITRE has shown that the problem can be solved by utilizing an array of adjunct apertures displaced from the main antenna. Extremely narrow notches can be realized by controlling both the diameter of the adjunct array and its separation from the main antenna as illustrated by the computer simulation of adapted pattern on the cover page labeled mainlobe cancellation. The results of these investigations are documented as part of the referenced Army contract.

## Section 2

### The MITRE Corporation: An Overview

The MITRE Corporation is an independent, not-for-profit organization operating in the public interest that conducts research and provides systems engineering and acquisition support to U.S. Government agencies. Although its largest activity assists the Department of Defense (DOD), the military services, and the intelligence community in system engineering programs for national security, MITRE also performs work for civil government agencies such as the Federal Aviation Administration (FAA), the Environmental Protection Agency, the Federal Bureau of Investigation, and the National Aeronautics and Space Administration.

MITRE's projects for the Department of Defense are performed in a Federally Funded Research and Development Center (FFRDC) under the primary sponsorship of the Assistant Secretary of Defense for Command, Control, Communications, and Intelligence, with sponsorship from the Air Force and the Army. MITRE carries out additional work for agencies in the civil sector of government, partly in another FFRDC under the sponsorship of the Federal Aviation Administration. MITRE is organized into a number of technical centers, each composed of several divisions. The adaptive processing capability spans across divisions and is concentrated in the Sensor Center.

The company does not compete with profit-seeking entities, nor does it have contractual relationships with commercial companies. Although MITRE builds experimental models as a

proof-of-concept stage for many of its systems programs, the company does not manufacture hardware or software. By refraining from commercial activity, MITRE maintains objectivity toward vendors and products, allowing the Corporation to serve as an impartial link between the government and competitive industry. MITRE concerns itself with all aspects of large and complex systems, including the areas of environment, energy, and the development, integration, and life-cycle support of sensor, communications, and information systems. In the national security area, these systems furnish command, control, communications, and intelligence capabilities for the military. For civil government agencies, similar capabilities involving the gathering, transfer, processing, and interpretation of data are provided. A strong state-of-the-art knowledge of technology underlies all of MITRE's work.

MITRE's highly technical work force and management provide both technical expertise and continuity of support to governmental programs. By sharing responsibility for program results, MITRE dedicates itself to ensuring the government's long-term program needs are met.

Dr. Barry M. Horowitz is MITRE's President and Chief Executive Officer and Mr. James R. Schlesinger is the Chairman of the Board. The Corporation's principal offices are in Bedford, Massachusetts, and McLean, Virginia, with additional sites elsewhere in the United States and overseas.

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## **Section 3**

### **Resumés**



**Edward Charles Barile**  
**Division D080**

**Education**

**M.S., Electrical Engineering, Northeastern University, 1971**  
**B.S., Electrical Engineering, Northeastern University, 1968**

**Employment History**

**1986 - Present: The MITRE Corporation, Bedford, MA**  
**1981 - 1986: ITEK Optical Systems, Lexington, MA**  
**1978 - 1981: MIT Lincoln Laboratory, Lexington, MA**  
**1972 - 1978: Naval Underwater Systems Center, Newport, RI**  
**1968 - 1970: Raytheon, Wayland, MA**

**Work Experience**

**1986 - Present: The MITRE Corporation, Bedford, MA, Member of the Technical Staff**

**Space-Time Adaptive Processing (STAP) for Detecting Targets in Clutter.** Mr. Barile developed an electromagnetic analysis of Displaced Phase Center Antenna (DPCA) and STAP for target detection from a moving platform. DPCA and STAP were shown to be filters in the wave number-frequency (space-time spectral) domain, and DPCA was shown to be a deterministic version of the more general STAP filter. The space-time spectral domain was used to analyze the performance of STAP and DPCA on clutter suppression, and the effects of clutter internal motion, and antenna-clutter-airframe interaction. The work includes a new formulation of the received field on a moving array in terms of cascaded impedance and admittance dyad operators which enables exact representation of the antenna-airframe interaction, mutual coupling, and also enables the expression of clutter multipath scattering. It was shown that the effect of antenna airframe interaction ("near field scattering") could be minimized but never completely removed. A method of preadaptive vertical near field suppression followed by line array STAP was developed by Mr. Barile, and shown to approach the performance of planar array STAP for some cases, thus significantly reducing the amount of processing.

Other investigations performed Mr. Barile include: multiple beam adaptive nulling antenna system analysis, motion emulation of Radar data from a fixed platform, conformal array pattern synthesis, Synthetic Aperture Radar methods of three-dimensional surface imaging, raid recognition with target classification, mutual coupling in dipole arrays and its compensation, low frequency active radar cross section simulation using crossed dipole reradiated fields, method of images for scattering from objects over a ground plane, and conformal vs. planar arrays for axial plane sidelobes.

**1981 - 1986: Itek Corporation (subsidiary of Litton Industries) Optical Systems Division, 10 Maguire Road, Lexington, MA.**

**Adaptive Optics.** Mr. Barile developed a theoretical analysis and computer simulation of a closed loop optical wavefront correction system using Kalman Filtering for actuator-controlled deformable mirrors. He also developed a method to concurrently estimate a poorly known or unknown observation matrix. This is essential for stable performance of the waveform correction system.

Mr. Barile also investigated: optical propagation, optical system analysis, non-paraxial analysis of focal plane fields, optical encoder analysis and simulation, CCD array image enhancement by masking, distorted image sequence restoration, reconstruction of wire frame (line delineated 3D objects from plane views), and grazing incidence telescope analysis for an X-ray telescope.

1978 - 1981: MIT Lincoln Laboratory, Lexington, MA, Technical Staff Member

Mr. Barile investigated: Kalman Filtering for reentry vehicle detection from shipborne (moving) radar, electromagnetic analysis of Synthetic Aperture Radar for imaging of rotating, precessing bodies, and its relationship to inverse scattering, endoatmospheric ray bending and elevation angle and range correction for trajectory estimation of targets at low altitudes, and distorted planar array analysis and correction.

1972 - 1978: Naval Underwater Systems Center, Newport, RI, Research Electrical Engineer.

Mr. Barile's work at the Naval Underwater Systems Center included: Underwater acoustics, active and passive signatures of submarines, surface ships, torpedoes, and their wakes, scale model measurements, acoustic scattering from periodic boundaries, near-in Doppler analysis, Space-Time Fourier Transform of Synthetic Aperture Sonar, acoustic propagation and scattering in a shallow channel, and hydrodynamics of underwater vehicles.

1968 - 1970: Raytheon Company, Wayland, MA, Microwave Antenna Design Engineer

**Antenna Design:** Mr. Barile developed an optimal way to group feed elements in a given uniformly spaced array to reduce the number of amplifier and phase shifter modules. He designed shaped beam reflectors for airport surveillance radars, and he did calculations of the near fields of a Cassegrainian antenna.

#### **Professional Society or Association Memberships**

Senior Member IEEE

#### **Professional Honors**

- Recipient of Special Recognition Award from D085 in 1992.
- MITRE Paper of the Year Award, 1993.

**Total Number of Journal or Conference Publications: 5**

#### **Journal or Conference Publications Related to Adaptive Processing**

Barile, E., Fante, R., Torres, J., "Some Limitations on the Effectiveness of Airborne Adaptive Radar," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 28, No. 4, October 1992.

Fante, R. L., Barile, E. C., Guella, T. P., "Clutter Covariance Smoothing by Subaperture Averaging," accepted for publication in *IEEE Transactions on Aerospace and Electronic Systems*, July 1994

Barile, E. C., Guella, T. P., Lamensdorf, D., "Adaptive Antenna Space-Time Processing Techniques to Suppress Wing Scattered Clutter for Airborne Radar," accepted for publication in *IEEE Transactions on Aerospace and Electronic Systems*, October 1994.

**Thomas Peter Bronez**  
**Division W090**

**Education**

**Ph.D., Electrical Engineering, Arizona State University (ARCS Fellowship), 1985**  
**M.S., Electrical Engineering, Virginia Tech (Pratt Presidential Fellowship), 1980**  
**B.S., Electrical Engineering, Virginia Tech (summa cum laude), 1979**

**Employment History**

**1990 – Present: The MITRE Corporation, McLean, VA**  
**1988 – 1990: SCOPE, Inc., Reston, VA**  
**1986 – 1988: Unisys Reston Technology Center, Reston, VA**  
**1985 – 1986: Signal-System Technology, Mesa, AZ**  
**1983 – 1984: Arizona State University, Tempe, AZ**  
**1981 – 1983: Bell Laboratories, Whippny, NJ**

**Work Experience**

**1990 – Present: The MITRE Corporation, McLean, VA**

Dr. Bronez is a Group Leader responsible for analysis, development, and evaluation of signal processing algorithms and systems. His current and past projects encompass radar signal processing and ECCM, target tracking, underwater acoustic transients, radio direction finding, beamformer design, signal design for LPI communications, and ESM system analysis. He performs project management and provides technical direction to project personnel.

**1988 – 1990: SCOPE, Reston, VA**

Dr. Bronez was a Senior Research Scientist, responsible for research and development of methods and systems for passive detection, estimation, classification, identification, and localization of signal emitters. He worked in ESM, ELINT, COMINT, and ASW. He performed field signal collection and scientific analysis of collected signals. He developed algorithms and performance predictions. He performed project management and supervised technical personnel.

**1986 – 1988: Unisys Reston Technology Center, Reston, VA**

Dr. Bronez was a Member of the Technical Staff. He performed research on signal processing and numerical mathematics, with application to fast algorithms, source localization and sensor array processing, parametric spectral analysis, robust estimation, and radar imaging. He developed a real-time COMINT system for localization and discrimination of HF emitters by high-resolution direction finding and adaptive filtering. He developed an inverse synthetic aperture radar (ISAR) analysis system for imaging of maneuvering airborne targets. He performed project planning and technical direction of personnel.

**1985 – 1986: Signal-System Technology, Mesa, AZ**

Dr. Bronez was a Consultant. He performed research on parametric and nonparametric methods for analysis of stationary and nonstationary signals having irregular sampling schemes. He developed methods for radar signature analysis and ISAR imaging of space-borne targets.

**1983 – 1984: Arizona State University, Tempe, AZ**

Dr. Bronez was a Research Assistant. He performed research on parametric spectral estimation methods, robust tracking of frequency-hop communication signals, and noise compensation for system identification.

**1981 – 1983: Bell Laboratories, Whippany, NJ**

Dr. Bronez was a Member of the Technical Staff. He developed digital filtering and spectral analysis algorithms and real-time software for a Navy passive sonar application. He delivered, integrated, and evaluated the system at its permanent field site.

**Teaching Experience**

**1990 – 1991: George Mason University, Fairfax, VA**, Dr. Bronez taught Detection and Estimation Theory as an adjunct faculty member

**1983 – 1984: Arizona State University, Tempe, AZ**, Dr. Bronez taught undergraduate circuit theory

**Software**

*Operating Systems:* CMS, MS-DOS, UNIX, VM, VMS

*Programming Languages:* APL, BASIC, C, FORTRAN, MATHEMATICA, MATLAB, X86 ASSEMBLER, TMS320X ASSEMBLER

*Applications:* EXCEL, LATEX, MATHEMATICA, MATLAB, WORD, WORD PERFECT, PERSUASION, TEX

*Development Tools:* SPW

**Professional Society or Association Memberships**

IEEE, Phi Kappa Phi, Tau Beta Pi, Eta Kappa Nu

**Licenses and Certifications**

EIT

**Foreign Languages**

German

**Total Number of Journal or Conference Publications: 15**

**Journal or Conference Publications Relating to Adaptive Processing**

Bronez, T., "MICL/EIL - An Effective Approach for Simultaneous Source Enumeration and ML Direction Finding," Submitted to *IEEE Seventh SP Workshop on Statistical Signal and Array Processing*, July 1994.

Keizer, R., T. Bronez, and J. Creekmore, "An Approximate Maximum Likelihood Algorithm for Direction Finding with Diversely Polarized Arrays," *Proc. MILCOM '93*, October 1993.

Bronez, T., et al., "Adaptive Beams for Beamspace Direction Finding," *Proc. IEEE Sixth SP Workshop Statistical Signal and Array Processing*, October 1992.



**Dean O. Carhoun  
Division D080**

**Education**

**Graduate Studies in Electrical Engineering, Massachusetts Institute of Technology, 1963-1967.  
B.S.E.E., Massachusetts Institute of Technology, 1958**

**Employment History**

**1960 – Present: The MITRE Corporation, Bedford, MA  
1958 – 1960: Vitro Corporation of America, West Orange, NJ**

**Working Experience**

**Mr. Carhoun is a Principal Engineer in the Surveillance Division of the Air Force C<sup>3</sup> Center. He joined MITRE in 1960 as a Member of the Technical Staff in the Electronic Warfare Department, supporting development of the SAGE air defense system. Since that time, he has contributed to a number of different technical areas, with a concentration in signal processing applied to radar, sonar, communications, and electronic warfare. He has held positions combining technical, project, and management responsibilities.**

**1992 – Present: As a Principal Engineer in the Surveillance Division, Mr. Carhoun was Project Leader and Principal Investigator for a technology program project in Matched-Field Adaptive Sensor Processing. He was engaged directly in the development of innovative adaptive signal processing techniques for underwater acoustic arrays used in ocean surveillance. Guiding the efforts of researchers in Bedford, Washington, and San Diego, he devised new adaptive beamforming techniques for both passive and active systems. His project team developed improved techniques of detection, classification, and localization based on these methods. He was responsible for planning follow-on business in this area. He supports MITRE-sponsored experimentation programs in wideband HF propagation and signal processing for over-the-horizon radar for wide area surveillance of cruise missiles.**

**1988 – 1992: As Associate Department Head, Signal Processing Concepts and Analysis Department in the Surveillance Division, Mr. Carhoun was co-responsible for the management, staffing, and direction of project efforts for a medium-sized technical department. He was responsible for proposing, planning, guiding, and directing the department's work in adaptive signal processing, mathematical research, and sensor array processing. He was Project Leader and Principal Investigator for projects in adaptive beamforming and residue number system signal processing. He initiated a new work area in adaptive array processing for radar and sonar applications. He participated in a study of ECM vulnerability of a proposed theater missile defense acquisition radar. He was responsible for contract monitoring and direction of a senior consultant (Dr. Irving S. Reed).**

**1984 – 1988: As Associate Department Head, Signal Processing and Electronic Warfare Department in the Surveillance Division, Mr. Carhoun was one of three associates responsible for assisting in the management of a large technical department engaged in wideband spread spectrum high frequency communications system development, technology program projects in mathematical research, residue number system signal processing techniques, VLSI custom design, and containing MITRE's VHSIC Technical Center. He was responsible for planning, guiding and directing the department's project work in mathematical research, RNS, and algebraic integer signal processing techniques. He was Project Leader for mathematical research, and Project Leader and Principal Investigator for advanced signal processing architecture. He led the**

development of RNS concepts and techniques for speech recognition, image compression coding, and matrix computations for adaptive beamforming. He was acting Group Leader of the Signal Processing and Mathematical Research Group (1984-1985). He restaffed the mathematical research program and recruited a new Group Leader. He was responsible for contract monitoring and direction of a senior consultant.

1979 – 1984: As Group Leader of the Signal Processing Techniques Group in the Signal Processing and Electronic Warfare Department, Mr. Carhoun was responsible for staffing and management of a technical group of 10 to 15 scientists and engineers. He was responsible for forming, staffing, and leading a new MITRE program in mathematical research. He was Project Leader for mathematical research, Project Leader and Principal Investigator for technology program projects in low cost electronics, LSI signal processing, sampled data processing, and CCD multilevel logic. He provided leadership and guidance of the group's research and publication efforts, as well as line management supervision and quality control of products. He led project efforts in the efficient decoding of algebraic error-correction codes. He was active in the publication of the group's work in error-correction decoding. He began exploratory work in the application of residue number system techniques to digital signal processing. He guided the research and publication efforts of mathematicians who conceived the use of extended algebraic integer rings for digital signal processing applications. He provided consultation in spread spectrum signal processing and error-correction coding implementation to the VHSIC SSEB.

1972 – 1979: As a Member of the Technical Staff in the Signal Processing and Electronic Warfare Department, Mr. Carhoun was responsible for task assignments in the areas of charge coupled device applications, low light level television for base installation security systems, integrated circuit development, system application and implementation of techniques for algebraic error-correction coding. He was Project Leader for the CCD multilevel logic and low-cost electronics projects. He provided consultation in spread spectrum signal processing to the SEEK TALK Phase II SSEB. He designed, developed, and tested a modular silicon intensified-target vidicon camera for base installation perimeter intrusion detection. He participated in an overseas on-site instrumented engineering design survey, and supported Air Force procurement of a SAFE NEST alarm verification system. He designed, built, and tested a high-resolution silicon vidicon camera for data capture in a MAC mechanized cargo terminal information retrieval application.

1970 – 1972: As a Member of the Technical Staff in the Defense Systems Department, Mr. Carhoun supported a nuclear survivability upgrade to an operational SAC system for emergency rocket communications. He was also responsible for the conceptual design, development, and operational test of a remotely deployable seismic vehicle detection and classification sensor. He devised an adaptive detection method and circuitry combining high detection sensitivity with negligible false alarm rate for that application.

1960 – 1970: As a Member of the Technical Staff in the Electronic Warfare and Optical Technology Department, Mr. Carhoun contributed to the development of concepts and techniques for passive detection of hostile aircraft to satisfy an ECCM requirement of the SAGE air defense system. He designed signal processing circuitry for an L-band bistatic cross-correlation interferometer. He provided support in system deployment strategies and costing to the SAGE/BUIC system program office. He supported DOD/WSEG in the ECCM performance analysis of tactical air defense radars. He designed, built, and tested a prototype S-band swept local oscillator receiver for use with a frequency-hopped air defense radar and supported the SAGE/BUIC system program office in subsequent procurement. He performed analyses for the SPACETRACK system program office on the AN/FSR-2 optical surveillance system. He subsequently developed theory and experimental techniques for extraction of information from unresolved optical signatures of orbiting satellites. He investigated techniques for image data compression in support of high resolution image data transmission for COMPASS LINK. He supported the Directorate of Foreign Technology, ASD, in the evaluation of foreign capabilities

and equipment in the areas of radar and electronic warfare. He supported an Air Force special purpose communications system, analyzing VLF communication channel characteristics and the corresponding performance of VLF spread spectrum digital communications systems.

**1958 – 1960: Vitro Corporation of America, West Orange, NJ**

**1958 – 1960: As an Electronics Engineer with Vitro's Laboratories Division, Mr. Carhoun designed and developed advanced solid-state circuitry for use in military radar and communications equipment.**

### **Hardware and Equipment**

**IBM PCs and 386/486 based systems, DEC mainframes, Sun workstations**

### **Software**

**MACSYMA, MATLAB, Mathematica, Maple V; UNIX and DOS operating systems; Microsoft Word, PowerPoint, Excel**

### **Professional Society Memberships**

**IEEE – Member, Professional Groups on Signal Processing, Information Theory, Antennas and Propagation, Oceanic Engineering.**

**Chairman, Boston chapter of the IEEE Information Theory Group, 1986.**

**Total Number of Journal or Conference Publications: 27**

### **Journal or Conference Publications Relating to Adaptive Processing**

**Carhoun, D. O., "Signal Subspace Projection Methods of Adaptive Sensor Array Processing," *Proceedings of the 27th Annual Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, November 1993.**

**Carhoun, D. O., "Subspace Projection Methods of Adaptive Array Processing," *IEEE Workshop on Underwater Acoustic Signal Processing*, University of Rhode Island, W. Greenwich, RI, October 1993.**

**Carhoun, D. O., "An Iterative Subspace Estimation Method for Adaptive Array Processing," *Proceedings of the 25th Annual Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, November 1991.**

**Carhoun, D. O., "Iterative Subspace Estimation Methods for Adaptive Array Processing," *IEEE Workshop on Underwater Acoustic Signal Processing*, University of Rhode Island, W. Greenwich, RI, September 1991.**

**Carhoun, D. O., "Adaptive Nulling and Spatial Spectral Estimation Using an Iterated Principal Components Decomposition," *Proceedings of the 1991 International Symposium on Acoustics, Speech and Signal Processing (ICASSP-91)*, Toronto Canada, May 1991. (Also presented in modified form at the *1991 Antenna Applications Symposium*, University of Illinois, September 1991.)**

Carhoun, D. O., Games, R. A., Townes, S. H., "A Principal Components Sidelobe Cancellation Algorithm," *Proceedings of the 24th Annual Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, November 1990.

Carhoun, D. O., "Adaptive Nulling of Transient Atmospheric Noise Received by an HF Antenna Array," *1990 Symposium on Antenna Applications*, University of Illinois, September 1990.

Carhoun, D. O., "RNS Signal Processing for Adaptive Beamforming," *RADC Symposium on RNS Technology*, Griffiss AFB, NY, August 1988.

**Richard Murray Davis  
Division D080**

**Education**

**B.A., Psychology, Syracuse University, 1975  
M.S., Electrical Engineering, Syracuse University, 1968  
B.S., Electrical Engineering, University of Rochester, 1964**

**Employment History**

**1990 – Present: The MITRE Corporation, Bedford, MA  
1966 – 1990: Syracuse Research Corporation, Syracuse, NY  
1964 – 1965: International Business Machines, Raleigh, NC**

**Work Experience**

**1990 – Present: The MITRE Corporation, Bedford, MA**

**Mr. Davis is a Principal Engineer in the Surveillance Division of the Center for Air Force C<sup>3</sup> Systems. He joined MITRE in 1990 after spending 24 years working for a small not-for-profit research facility in a university campus environment, where he developed expertise in electronic counter-countermeasures (ECCM).**

**1992 – Present: Mr. Davis is currently leading a three-man countermeasures analysis effort sponsored by the Ground Based Radar (GBR) Project Office within the U.S. Army Strategic and Space Defense Command (USASSDC) in Huntsville, Alabama. The objective of the project is to develop and recommend ECCMs and anti-radiation missile (ARM) countermeasures for the X-band theater and national missile defense (TMD and NMD) radars currently being manufactured by the Raytheon Company.**

**Mr. Davis also spends about one-quarter of his time working on a special project.**

**1991 – 1992: One of Mr. Davis's primary tasks during this period was to contribute toward the development of a jamming technique (Adaptive Cross-Eye) which could be used by an aircraft or ground radar to ward off (turn) an attacking missile. The technique creates angle deception in the missile seeker. The technique was developed under a MITRE-sponsored research (MSR) program. Mr. Davis has subsequently played a leading role in marketing and attempting to transfer the new technology to other agencies.**

**1966 – 1990: The Syracuse Research Corporation, Syracuse, NY**

**1985 – 1990: During this period, Mr. Davis managed a technical center that specialized in signal processing relating to radar, ECM, ECCM, and emitter location. Mr. Davis also acted as the project engineer for an ECM/ECCM Analysis contract that the center had with the Ground-Based Radar (GBR) Project Office within the U.S. Army Strategic Defense Command. Other contractual activities within the center involved optical correlation processing and the development of residue number system processing algorithms.**

**During the 1985-1989 period, Mr. Davis led a team of researchers who did pioneering work in the area of orthogonal weight perturbation algorithms for adaptive arrays. The perturbation techniques fall under the category of single-port adaptive algorithms. They eliminate the need**

for having separate receivers for each auxiliary element in an adaptive array. During the same period, he invented a new concept scanning reflector. The new architecture consisted of a parabolic reflector fed by an offset phased array. Mr. Davis invented a novel method for feeding the array using a space feed. The antenna supports multi octave tunable bandwidths and instantaneous bandwidths in excess of a gigahertz without resorting to time-delay steering.

During the 1985-1989 time period, Mr. Davis also directed an effort to determine the feasibility of using optical correlation processing in the receive and image planes to determine the size, shape, and motion of space objects being illuminated by a laser. Some experiments were conducted at the University of Rochester.

**1978 – 1985:** Between 1978 and 1985, Mr. Davis acted as program manager on a number of technology development programs with the U.S. Army Strategic Defense Command in Huntsville, Alabama. The focus of these programs was on synthesis of ECM threats to ballistic missile defense systems, assessment of radar defense vulnerability, and the development of new ECCM techniques. Engagement simulations which model threats, as well as radar operating modes including surveillance, acquisition, and tracking, were developed. The simulations included polynomial and Kalman tracking filters. Extensive simulation work was also performed in the area of antenna pattern analysis. Many ECCM techniques were also modeled. ECCM techniques which were modeled included: a time-difference-of-arrival (TDOA) passive tracking system, sidelobe and mainlobe cancellation, sideflash, and radar shutdown in defense against radiation homing missiles.

Between 1979 and 1981, Mr. Davis was the project engineer on a Sidelobe Canceller-Sidelobe Blanker Compatibility Study for the AEGIS system (sponsored by the Naval Surface Weapons Center, Dahlgren Laboratory). Recommendations were made pertaining to the operation of sidelobe cancellers with the difference beams in order to preclude degradation in sidelobe blanker operation.

**1972 – 1978:** Mr. Davis acted as the project engineer on an ECM/ECCM Analysis contract with the Site Defense Radar Project Office (sponsored by the Army in Huntsville, Alabama) between 1974 and 1976. Under this effort, he recommended changes in the way that the canceller was implemented on the sum and difference beams which resulted in a significant cost saving. During this period, Mr. Davis also provided consulting in the area of adaptive processing on a number of other radar weapon systems for the Army, Navy, and Air Force, including PATRIOT (Army Missile Command).

**1966 – 1972:** Between 1966 and 1972, Mr. Davis assisted in the design, fabrication, testing, and performance analysis of a number of sidelobe canceller systems. He built analog and digital hardware and helped in field testing. He made swept frequency response measurements on a number of large antennas around the country in an effort to better understand sources of decorrelation and antenna errors. Included in the measurements were the HAPDAR array at White Sands Missile Range, the HIPSAF antenna developed by Hughes, and the FPS-40B Navy surveillance dish antenna. During this period, Mr. Davis also examined the feasibility of performing narrowband range-Doppler imaging.

**1964 – 1965:** The International Business Machines, Raleigh, NC

During 1964 and 1965, while working for IBM, Mr. Davis helped design a multiplexor interfacing between a System 360 computer and many transmission lines. He designed logic circuits to recognize message formats and perform error detection of incoming and outgoing data.

## **Hardware and Equipment**

Mr. Davis has fabricated a number of different types of microwave filters, including one which he invented. He has field experience in measuring sidelobes and frequency responses of microwave antennas. He has fabricated jammers and built some digital hardware.

## **Software**

Mr. Davis programs in FORTRAN and has taken a number of courses in "C". He is familiar with Macintosh and IBM PCs and VAX computers. He is also fluent in WordPerfect and Microsoft Word.

## **Professional Society or Association Memberships**

Mr. Davis is a senior member of the Institute of Electrical and Electronic Engineers (IEEE).

## **Patents**

United States Patent SIR Serial 07/441,749: Mainlobe Canceller with Motion Compensation for Use with Radar Systems, with P. Sanyal, filed 27 November 1989.

A number of SECRET inventions were disclosed to the Army. In addition, two error detection circuits were disclosed while working at IBM.

## **Total Number of Journal or Conference Publications: 12**

### **Journal or Conference Publications Relating to Adaptive Processing**

Davis, R. M., and Talbot, P. J., "LMS Adaption with Hard-limited Gradient," *IEEE AP-S International Symposium*, Vol. III, pp. 992-995, 1988.

Davis, R. M., Farden, D. C., and Sher, J. S., "Adaptivity for Multibeam Antennas Using Coupled Weights," *MILCOM '86 Conference Record, Classified Volume*, October 1986.

Davis, R. M., Farden, D. C., and Sher, J. S., "A Coherent Perturbation Algorithm," *IEEE Trans. Ant. and Prop.*, AP-45, No. 3, March 1986.

Davis, R. M., Farden, D. C., "Orthogonal Weight Perturbation Algorithms in Partially Adaptive Arrays," *IEEE Trans. Ant. and Prop.*, AP-33, No. 1, January 1985.

Davis, R. M. and Sher, J. S., "Quantization Noise in Adaptive Weighting Networks," *IEEE Trans. AES*, AES-10, No. 5, September 1984.

Davis, R. M. and Gleich, J., "Element Placement in Adaptive Arrays and Sidelobe Cancellers," *Proceedings of Symposium on Adaptive Antennas*, July 1980.

Davis, R. M., "Mainlobe Cancellation Using Peripheral Subarrays," *Twenty-third Annual Tri-Service Symposium Record*, 1977.



**Robert Charles DiPietro**  
**Division D080**

**Education**

**M.S., Electrical Engineering, University of Connecticut, 1974**

Thesis: "A General Purpose Computer Based Controller System"

**B.S.E., Electrical Engineering, with highest Honors, University of Connecticut, 1969**

**Employment History**

**1985 – Present: The MITRE Corporation, Bedford, Massachusetts**

**1980 – 1985: AT&T Bell Telephone Laboratories, North Andover, Massachusetts**

**1977 – 1980: The Analytic Sciences Corporation (TASC), Reading, Massachusetts**

**1972 – 1977: United Technologies Research Center, East Hartford, Connecticut**

**Work Experience**

**1985 – Present: The MITRE Corporation, Bedford, Massachusetts**

Mr. DiPietro is a member of the technical staff in the Adaptive Processing Group of Department D088, Advanced Systems, and has focused on forward looking applications of digital signal processing in communications and radar systems. Early assignments were in support of the MITRE WBHF (wideband high frequency) initiative and involved performance prediction analyses of both time (adaptive transversal filter) and frequency domain (FFT based excision) narrowband interference canceller subsystems. The adaptive beamforming and direction finding areas were next explored to assess tradeoffs of various adaptive spatial nulling methods and super-resolution direction-of-arrival estimation techniques. Particular emphasis was placed on the problem of nulling (estimating) highly correlated signal sources. In the related area of wideband array steering for large random arrays, a study was completed that provided a defendable set of design tradeoffs for the digital interpolation and phase correction parameters which was then used to define candidate architectures of a VLSI based steering system. For the last several years, this adaptive array work has focused on radar applications. So-called space-time processing concepts are being considered to ameliorate spread clutter effects in future airborne surveillance radar systems and thereby improve detection performance. Completed and ongoing studies have addressed the nature of the spread clutter effects from recorded data, and are assessing candidate algorithms performance. A suboptimal space-time architecture, based on transform domain techniques, has been developed to reduce the complexity of true optimal processing. This technique has demonstrated superior performance among competing algorithms. Current assignments include development of wide area high resolution SAR imaging and automated target recognition algorithms.

**1980 – 1985: AT&T Bell Telephone Laboratories, North Andover, Massachusetts**

As a member of the technical staff, assignments were focused on the application of new digital signal processing concepts to telephone transmission issues. Specific project areas include algorithm development and evaluation of low bit rate speech encoding schemes; adaptive filtering algorithms for echo canceller systems; modeling and characterization (system identification) studies of transmission system dynamics; and a number of other related modeling,

simulation, and performance evaluation tasks. Much of this work made use of a real-time simulation facility and required the development of original software in both high- and low-level languages.

#### **1977 – 1980: The Analytic Sciences Corporation (TASC), Reading, Massachusetts**

Mr. DiPietro was a member of the technical staff in the Controls Division involved in a number of defense related programs. He performed analytic studies for the Air Force Weapons Laboratory in the high energy laser area involving atmospheric turbulence and thermal blooming effects. Other Air Force programs required evaluation of new terminal correlation guidance concepts for cruise missiles. In a Navy study, the feasibility of using the Space Shuttle to test guidance systems for submarine launched missiles was explored. Other work at TASC under Army sponsorship includes the development of a six degree-of-freedom exo-atmospheric missile intercept simulation using statistical linearization techniques.

#### **1972 – 1977: United Technologies Research Center, East Hartford, Connecticut**

Employed as Research Engineer in the Controls and Simulation Group, Engineering Analysis Section. Responsibilities focused on applying multivariable control and estimation techniques to overall system design problems. Particular applications included advanced design propulsion systems, VTOL flight vehicles, and active optics control systems. Involved in the design and implementation of real-time digital control systems for automotive diagnostics and active optics beam control systems.

#### **Teaching Experience**

Mr. DiPietro was a teaching assistant at the University of Connecticut in the 1970–1971 academic year.

#### **Hardware/Equipment**

**Sun workstations, Macintosh, IBM PCs, DEC VAX, IBM and Univac mainframes**

#### **Software**

***Operating Systems: UNIX, MacOS, PC DOS, IBM JCL***

***Programming Languages: FORTRAN, C, BASIC, APL***

***Applications: MS Word, TeXtures, MacDraw Pro, MATLAB***

***Communications /Network, Protocols, Standards, or Software: Versa-Term Pro, KERMIT***

#### **Professional Society or Association Memberships**

**I.E.E.E.**

**Tau Beta Pi**

**Eta Kappa Nu**

**Phi Kappa Phi**

**Amateur Radio License (Advanced)**

## **Professional Honors**

While at the University of Connecticut, was designated "University Scholar" in 1968, and received the Klopp Memorial Prize (for undergraduate achievement in mathematics) 1967.

**Total Number of Journal or Conference Publications: 3**

### **Journal or Conference Publications Relating to Adaptive Processing**

DiPietro, R. C., "Extended Factored Space-Time Processing for Airborne Radar," *Twenty-Sixth Annual Asilomar Conference on Signals, Systems and Computing*, Pacific Grove, CA, pp. 525-530, October 1992.

DiPietro, R. C., "An FFT-Based Technique for Suppressing Narrowband Interference in PN Spread Spectrum Systems," *IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP'89*, Glasgow, U.K, May 1989.



**Ronald L. Fante**  
**Division A030**

**Education**

**Ph.D., Electrical Engineering, concentration in Plasma Physics, Princeton University, 1964**  
**M.S.E.E., Electrical Engineering, concentration in Electromagnetics, Massachusetts Institute of Technology, 1960**  
**B.S.E.E., Electrical Engineering, University of Pennsylvania, 1958**

**Employment History**

**1988 – Present: The MITRE Corporation, Bedford, MA**  
**1980 – 1988: Textron Defense Systems, Wilmington, MA**  
**1971 – 1980: Rome Laboratories, Hanscom AFB, MA**  
**1964 – 1971: Avco Systems Division, Wilmington, MA**  
**1963 – 1964: Space Sciences Corporation, Waltham, MA**

**Work Experience**

**1988 – Present: The MITRE Corporation, Bedford, MA**

**Dr. Fante is a MITRE Fellow in the Bedford Group. Since 1988 he has been leading studies on adaptive airborne radar, detection statistics for over-the-horizon radar, radar bistatic clutter modeling, antenna capabilities analysis and electromagnetic wave interactions with matter.**

**1980 – 1988: Textron Defense Systems, Wilmington, MA**

**As Assistant Vice President of Engineering, Dr. Fante led efforts on FM/CW radar, millimeter wave radar, infrared detection and imaging, electronic countermeasure studies, antenna radiation and coupling in a plasma environment, design of low radar cross section targets and laser propagation.**

**1971 – 1980: Rome Laboratory, (Air Force Cambridge Research Laboratory prior to 1977), Hanscom AFB, MA**

**As Senior Scientist he performed detailed analyses of tactical radars, radomes, digital signal processors, microwave devices, antennas, space-based radars and laser propagation in the atmosphere. One of his accomplishments was the first theoretical explanation of the saturation of light fluctuations in the turbulent atmosphere. He also designed one of the first antenna systems with all measured sidelobes below -50 dB.**

**1964 – 1971: Avco Systems Division, Wilmington, MA**

**As a Senior Engineer he performed advanced research on reentry physics, antennas, microwave devices, propagation of electromagnetic waves, microwave breakdown, and target radar cross sections. He was the inventor of the "thin sheath approximation" which was universally used to predict attenuation and antenna isolation on reentry vehicles.**

**1963 – 1964: Space Sciences, Waltham, MA**

**As a research engineer, Dr. Fante studied electromagnetic wave propagation in a nuclear environment and modeled kinetic flow around aerodynamic vehicles.**

## **Teaching Experience**

**Dr. Fante was an instructor at Tufts University in 1982, at Northeastern University in 1965, and served as Adjunct Professor of Electrical Engineering at the University of Massachusetts, Amherst, from 1973 to 1980.**

## **External Technical Committee Memberships**

**IEEE Fellows and Awards Committee, Chairman 1992–  
IEEE National Fellows Committee, member 1989–1992  
IEEE Transactions on Antennas and Propagation, Editor in Chief, 1983–1986  
IEEE Antennas & Propagation Society, Administrative Committee, 1979–1982  
IEEE Antennas & Propagation Society, Chairman Boston Section, 1973  
International Union of Radio Science, Membership Chairman 1982–1985  
Accreditation Board for Engineering, member 1983–1985  
National Research Council Steering Committee for Army Basic Research, member 1986–1988**

## **Professional Society or Association Memberships**

**IEEE – Fellow  
Optical Society of America – Fellow  
Electromagnetics Academy  
International Union of Radio Science**

## **Professional Honors**

**Atwater Kent Prize, 1958  
Marcus O'Day Prize, 1975  
IEEE Antennas & Propagation Society Best Paper Award, 1980  
USAF Department of Laboratories Achievement Award, 1974  
USAF Achievement Award 1972, 1973, 1974, 1975, 1976, 1977, 1978, 1979, 1980  
I Migliori Award for Outstanding Achievement by an American of Italian Ancestry, 1989  
Listed in "Who's Who in America"**

## **Patents**

**United States Patent 4,135,185 and 4,213,122: Intruder Detection Systems, 1979**

## **Total Journal and Conference Publications: 174**

### **Journal Publications**

**Antenna Theory – 20 papers  
Electromagnetic Theory – 7 papers  
Electromagnetic Scattering – 11 papers  
Microwave Breakdown – 12 papers  
Plasma Physics – 4 papers  
Propagation and Imaging in Random Media – 48 papers  
Radar Detection – 8 papers  
Reentry Effects on Antennas – 8 papers  
Signal Processing – 1 book entitled, "Signal Analysis & Estimation," Wiley, 1988.  
Wave Propagation – 7 papers  
Adaptive Processing – 5 papers**

### **Journal or Conference Publications Relating to Adaptive Processing**

**Fante, R. L., "Cancellation of Specular and Diffuse Jammer Multipath Using a Hybrid Adaptive Array," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 27, pp. 823-837, September 1991.**

**Fante, R. L., Barile, E. C., Torres, J. A., "Some Limitations on the Effectiveness of Airborne Adaptive Radar," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 20, pp. 1015-1032, October 1992.**

**Fante, R. L., Barile, E. C., Guella, T. P., "Clutter Covariance Smoothing by Subaperture Averaging," to appear in the October 1994 issue of the *IEEE Trans. on Aerospace and Electronic Systems*.**

**Fante, R. L., Torres, J. A., "Cancellation of Diffuse Jammer Multipath by an Airborne Adaptive Radar," accepted for publication in the *IEEE Trans. on Aerospace and Electronic Systems*.**

**Fante, R. L., DiPietro, R. C., Torres, J. A., "Cancellation of Diffuse Jammer Multipath—Suboptimum Frequency Space Processing," submitted to *IEEE Trans. on Aerospace and Electronic Systems*, 1994.**



**Richard A. Games  
Division D050**

**Education**

**Ph.D., Mathematics, concentration in Combinatorics, Ohio State University, 1980**  
**M.S., Mathematics, Ohio State University, 1977**  
**B.S., Mathematics, Carnegie-Mellon University, 1974**

**Employment History**

**June 1984 – Present: The MITRE Corporation, Bedford, MA**

**June 1981 – June 1984: Colorado State University, Fort Collins, CO**

**Summer 1982: Institute for Defense Analysis, Princeton, NJ**

**September 1978 – June 1981: The Ohio State University, Columbus, OH**

**Summers 1979, 1980: The MITRE Corporation, Bedford, MA**

**June 1977 – September 1978: The MITRE Corporation, Bedford, MA**

**September 1975 – June 1977: The Ohio State University, Columbus, OH**

**Work Experience**

**June 1984 – Present: The MITRE Corporation, Bedford, MA**

Dr. Games is a Principal Scientist in the Communications Division, D050 in the Center for Air Force C<sup>3</sup> Systems. He is also acting Group Leader of the Mathematical Research and Applications Group in the Signal Processing Department, D051, where he manages five staff members. He joined MITRE in 1984 after four years of university teaching and research in mathematics. Dr. Games is an expert in combinatorics, combinatorial design theory, graph theory, finite fields, and linear algebra. Dr. Games is currently project leader of the three-staff Mathematical Research project, which supports long-range mathematical research in areas that impact communications and signal processing, and the .5 staff Nonlinear Models of Analog-to-Digital Converters project, which is developing compensation techniques for the errors produced by high-performance analog-to-digital converters.

In the past, Dr. Games has been the project leader for efforts that have applied new number representations to improve the performance of digital signal processors, have investigated the applicability of neural networks to signal processing, and have developed advanced systolic array architectures for digital signal processors. The focus of this last effort was the real-time implementation of matrix decomposition algorithms used in adaptive signal processing. Dr. Games and his team developed new approaches for efficiently performing adaptive sidelobe cancellation that are currently being implemented in a real-time system. Dr. Games also has performed theoretical analysis and off-line experimentation of adaptive antenna array algorithms, and is currently the point of contact for applying the real-time sidelobe canceller that is currently under development. Dr. Games also maintains a program of mathematical research in the areas of the correlation and complexity properties of sequences used in communications, radar, and

cryptography. His recent work has involved developing techniques for recovering noisy sequences that have applications to spread spectrum communications and stream ciphers.

**June 1981 – June 1984: Colorado State University, Fort Collins, CO**

Dr. Games was an Assistant Professor in the Department of Mathematics where he performed research in combinatorics and taught courses in applied algebra and combinatorics at both the undergraduate and graduate level. He supervised two master degree students.

**Summer 1982: Institute for Defense Analysis, Princeton, NJ**

Dr. Games participated in the summer SCAMP program as a mathematician.

**September 1978 – June 1981: The Ohio State University, Columbus, OH**

Dr. Games was a graduate teaching assistant in the Department of Mathematics while in school. He became a Lecturer for one year after obtaining his Ph.D.

**Summers 1979, 1980: The MITRE Corporation, Bedford, MA**

Dr. Games was a Member of the Technical Staff in the Electronic Warfare Department, D082. He performed research in error-correcting codes and sequence complexity.

**June 1977 – September 1978: The MITRE Corporation, Bedford, MA**

Dr. Games was a Member of the Technical Staff in the Advanced Planning Department, D053. He developed battle simulations to assess the performance of advanced tactical concepts. He also was the project leader of a small research effort in error-correcting codes.

**September 1974 – June 1977: The Ohio State University, Columbus, OH**

Dr. Games was a teaching assistant in the Department of Mathematics while in graduate school. He had a University Fellowship his first year and did not teach. In subsequent years he assisted in a variety of undergraduate courses.

**Teaching Experience**

Dr. Games taught undergraduate and graduate level mathematics courses in algebra and combinatorics at the Colorado State University. He taught calculus and discrete mathematics courses as an instructor and a graduate student at the Ohio State University (see work experience, above).

**Professional Society or Association Memberships**

American Mathematical Society

International Association for Cryptologic Research

The Institute of Electrical and Electronic Engineers (IEEE)

**Professional Honors**

Tau Beta Pi, Phi Kappa Phi, Ohio State University Fellow (1974-1975)  
1990 MITRE Best Paper Award

## Foreign Languages

Dr. Games can read the technical literature in French and German.

**Total Number of Journal or Conference Publications: 32**

### Journal or Conference Publications Relating to Adaptive Processing

Games, R. A., Rorabaugh, T. L., "Wide-Bandwidth HF Noise Mitigation Using a Real-Time Adaptive Sidelobe Canceller," *Proceedings of MILCOM '93*, Boston, MA, 1993.

Games, R. A., Eastman, W. L., Sousa, M. J., "Fast Algorithm and Architecture for Constrained Adaptive Sidelobe Cancellation," *IEEE Transactions on Antennas and Propagation*, Vol. 41, pp. 683-686, 1993.

Games, R. A., Townes, S. A., Williams, R. T., "Experimental Results of Wide-Bandwidth High-Frequency Adaptive Array Processing," *Proceedings of MILCOM*, San Diego, CA, pp. 294-300, November 1992.

Games, R. A., Townes, S. A., Williams, R. T., "Experimental Results for Adaptive Sidelobe Cancellation Techniques Applied to an HF Array," *Proceedings of the 25th Annual Asilomar Conference on Signals, Systems and Computers*, Monterey, CA, pp. 153-159, November 1991.

Games, R. A., Eastman, W. L., Sousa, M. J., "Fast Algorithm and Architecture for Constrained Adaptive Sidelobe Cancellation," *Proceedings of SPIE: Advanced Signal Processing Algorithms, Architectures, and Implementations II*, San Diego, CA, pp. 322-328, July 1991.

Games, R. A., Williams, R. T., "Performance Analysis of a Concurrent Adaptive Least-Squares Sidelobe Cancellation System with Excess Degrees of Freedom," *Proceedings of the IEEE International IEEE/AP-S Symposium*, London, Ontario, Canada, pp. 86-89, June 1991.

Eastman, W. L., Games, R. A., Sousa, M. J., "Multiple Mainbeam Sidelobe Cancellation Architectures for Constrained and/or Excess Degrees of Freedom Processing," *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, Toronto, Canada, pp. 1589-1592, May 1991.

Carhoun, D. O., Games, R. A., Williams, R. T., "A Principal Components Sidelobe Cancellation Algorithm," *Proceedings of the 24th Annual Asilomar Conference on Signals, Systems and Computers*, Monterey, CA, pp. 763-768, November 1990.



**Thomas Paul Guella**  
**Division D080**

**Education**

**Ph.D., Physics, concentration in Atomic and Laser Physics, New York University, 1985**  
**M.S., Physics, New York University, 1980**  
**B.S., Physics and Mathematics, Hunter College, C.U.N.Y., 1977**

**Employment History**

**1989 – Present: The MITRE Corporation, Bedford, MA**  
**1985 – 1989: MIT Lincoln Laboratory, Lexington, MA**  
**1980 – 1985: New York University Physics Department, New York, NY**  
**1977 – 1980: New York University Physics Department, New York, NY**

**Work Experience**

**1989 – Present: The MITRE Corporation, Bedford, MA**

Dr. Guella's work during this period was directed toward three areas of research. The first investigations pertained to the development of new airborne surveillance radars using Geometrical Theory of Diffraction (GTD) numerical methods. GTD was utilized in order to determine the effect that the airframe platform has on ultralow sidelobe performance and on the ability of adaptive processing methods to cancel clutter and jamming. During this time, Dr. Guella was also involved in a study to quantify the predictive accuracy of the GTD numerical codes when they are applied to large on-platform ultralow sidelobe antenna arrays. Using the GTD code and an elliptical array excitation synthesis procedure he wrote, he was able to demonstrate the GTD code's accuracy against measured data of a 1:7 scale 707 platform mounted antenna. A second area of research was concerned with the development of advanced adaptive processing methods for jammer and clutter rejection in airborne radars. As a result of these investigations, Dr. Guella adopted a procedure used previously by the spectral estimation community, called subaperture averaging, and applied it to the airborne radar problem with very successful results. Using subaperture averaging, he was able to solve the discrete correlated interference problem, when present in the airborne radar environment. He also showed that subaperture averaging can be used with great success for estimation of the sample covariance matrix when very few data samples are available for matrix estimation. During this time also, Dr. Guella developed a procedure for synthesizing both near field and far field pattern nulls on conformal antenna arrays. Finally, in support of a ground based radar (GBR) project, Dr. Guella developed a procedure for synthesizing wideband, wide angular pattern sector notches for large planar antenna arrays composed of contiguous subarrays that employ both phase steering and time delay steering.

**1985 – 1989: MIT Lincoln Laboratory, Lexington, MA**

As a staff member at Lincoln, Dr. Guella was actively involved in the analytical development of algorithms pertaining to null steering in antenna arrays. This work entailed both the synthesis of a priori-notched patterns and the implementation of adaptive processing techniques, most notably those techniques involving Sample Matrix Inversion. Dr. Guella's work dealt primarily with the theoretical evaluation of the effects that a particular class of phase errors have on the performance of such algorithms and synthesis methods, and their effectiveness in maintaining jammer resistance and the overall pattern integrity when these errors are present.

### **1980 – 1985: New York University Physics Department, New York, NY**

Dr. Guella held a doctoral research assistantship in the Atomic Beams Laboratory as part of the doctoral requirement. Responsibilities included the operation and maintenance of complex, high-vacuum systems and electronic equipment, and the measurement of atomic and molecular polarizabilities by atomic beam spectroscopic methods. During this period Dr. Guella also designed necessary components for the experimental apparatus, including a hexapole electromagnet, a high temperature neutral beam oven, and a quadrupole mass filter.

### **1977 – 1980: New York University Physics Department, New York, NY**

During this period Dr. Guella held a Teaching Assistantship at NYU. Work included the preparation and teaching of physics recitation classes and laboratory sessions. Typical teaching load involved approximately 12 hours per week.

#### **Teaching Experience**

Dr. Guella taught one semester of freshman physics at the Brooklyn campus of Long Island University in the spring of 1985. In addition, he taught physics recitation classes and laboratory sessions at New York University (see work experience above).

#### **Hardware and Equipment**

**IBM PCs, IBM 3081 Mainframe, VAX 6000 series Mainframe, VAX 9000 series Mainframe, Sun Workstations**

#### **Software**

***Operating Systems:* VAX VMS, IBM VM/CMS, PC DOS, some UNIX, some Sun/OS**

***Programming Languages:* FORTRAN, BASIC, RATFOR, some C**

***Applications:* WordPerfect, Easyplot, Graftools, NEC-BSC GTD numerical code**

***Teleprocessing Monitors and Environments:* MS WINDOWS**

#### **Professional Honors**

Recipient of Special Recognition Award from D085, 1992.

Recipient of the Gillet Memorial Prize in 1977 from Hunter College for outstanding achievement in mathematics

#### **Total Number of Journal or Conference Publications: 4**

##### **Journal or Conference Publications Relating to Adaptive Processing**

Fante, R. L., Barile, E. C., Guella, T. P., "Clutter Covariance Smoothing by Subaperture Averaging," accepted for publication in *IEEE Transactions on Aerospace and Electronic Systems*, July 1994

Barile, E. C., Guella, T. P., Lamensdorf, D., "Adaptive Antenna Space-Time Processing Techniques to Suppress Wing Scattered Clutter for Airborne Radar," accepted for publication in *IEEE Transactions on Aerospace and Electronic Systems*, October 1994.

**J. David R. Kramer, Jr.**  
**Division D080**

### **Education**

**ScD, Electrical Engineering, concentration in Control and System Optimization Theory, Massachusetts Institute of Technology, 1964**  
**M.S.E.E., Electrical Engineering, concentration in Linear Circuit Theory, Massachusetts Institute of Technology, 1958**  
**B.S.E.E., Electrical Engineering, University of Pennsylvania, 1957**

### **Employment History**

**1964 – Present: The MITRE Corporation, Bedford, MA**  
**1957 – 1964: Instructor and Graduate Student, Massachusetts Institute of Technology, Cambridge, MA**  
**1958: Summer Staff Member, RAND Corporation, Santa Monica, CA**

### **Work Experience**

Dr. Kramer joined The MITRE Corporation in 1964 and has held various technical and management positions since that time. In 1983 he was appointed as MITRE's first Consulting Scientist. His working experience covers a large variety of radar and communications problems. His current interests include array signal processing, propagation in non-homogeneous media, and the application of radar techniques to subsurface imaging.

**1990 – Present: The MITRE Corporation, Bedford, MA**

Dr. Kramer is leader of the MITRE Sponsored Research project, "High-Resolution Noise Mitigation Measurements." High frequency atmospheric noise data is being collected by a 96-element array and processed to characterize the extent to which the noise may be mitigated by adaptive array processing. Dr. Kramer is also leading a corporate initiative on the application of ground-penetrating radar to the hazardous waste remediation problem. He also serves as a part-time consultant and advisor to several radar acquisition programs.

**1988 – 1989: Project Leader of a MOIE investigation of the application of track-before-detect methods to the detection of weak targets. During this period, Dr. Kramer also worked on signal processing concepts for the advanced over-the-horizon radar project for the Air Force and DARPA.**

**1987 – 1988: Project Leader, Wideband OTH Radar Experimentation. Recordings of one megahertz wideband high frequency signals were made at widely spaced locations to characterize the spatial and temporal behavior of ionospheric propagation. During this period, Dr. Kramer also participated in the Air Defense Initiative (ADI) program under Air Force sponsorship.**

**1982 – 1986: During this period, Dr. Kramer worked on a classified project as a member of the Intelligence and Naval Operations Division.**

**1979 – 1983:** Associate Department Head in D86, Dr. Kramer was Project Leader of a MITRE sponsored adaptive antenna technology project which built a hybrid adaptive antenna simulation and processor. He was also heavily involved with the SEEK TALK and JTIDS communications projects for the Air Force. These programs relied heavily on spread spectrum and adaptive processing technology.

**1969 – 1979:** Group Leader in D82. Dr. Kramer worked on radar design, statistical analysis, and signal processing. The work involved trajectory analysis, propagation, target cross-section statistics, and automatic detection and tracking algorithms. Dr. Kramer participated in the conceptual design and siting studies of the USAF PAVE PAWS radar system. He also participated in tracker design for the USAF OTH experimental radar system, and the conceptual design and system analysis of an artillery locating radar for the U.S. Army.

**1964 – 1969:** As a member of the technical staff, Dr. Kramer worked under DARPA sponsorship on problems of space object identification and ballistic missile defense.

### **Teaching Experience**

Dr. Kramer was an instructor in the Department of Electrical Engineering at Massachusetts Institute of Technology (1960–1964).

Dr. Kramer lectured at Northeastern University (1965–1966).

Dr. Kramer lectured for the MITRE Institute. Topics have included Digital Communications (1976), HF Communications (1980), Adaptive Antennas (1982), Introduction to HF Propagation (1985), and Wave Propagation (1992).

### **Hardware and Equipment**

Dr. Kramer is experienced in the use of modern electronic laboratory equipment such as spectrum analyzers, signal generators, impedance bridges, and digital data acquisition systems. He is also familiar with IBM and Macintosh personal computers, DEC, HP minicomputers, and various mainframes.

### **Software**

*Programming Languages:* Assembly language, FORTRAN, and Basic. Dr. Kramer is the designer of COVARI and several other radar simulation and trajectory analysis tools.

### **External Technical Committee Memberships**

Member of 1966 IDA Summer Study on Ballistic Missile Defense

Member of 1978 MX Survivability Study conducted by Chief Scientist, USAF

Member of 1981 AJ Communications Interoperability Group (Joint AF–Navy)

Member of 1982 AF Blue Ribbon AJ Communications Study chaired by Chief Scientist, USAF

Member of 1990 DARPA Ultra-Wideband Study Panel

Member of MITRE Patent Committee

### **Professional Society or Association Memberships**

**Tau Beta Pi**  
**Eta Kappa Nu**  
**Sigma Xi**  
**Institute of Electrical and Electronic Engineers**

### **Total Number of Journal or Conference Publications: 12**

#### **Journal or Conference Publications Relating to Adaptive Processing**

**Kramer, J. D. R., Jr., R. T. Williams, "High-Frequency Atmospheric Noise Mitigation," *Proceedings of ICASSP 1994*, April 1994.**

**Kramer, J. D. R., Jr., W. S. Reid, "Track-Before-Detect Processing for a Range-Ambiguous Radar," *Proceedings of the 1993 IEEE National Radar Conference*, April 1993.**

**Kramer, J. D. R., Jr., "A Flexible Adaptive Antenna Facility," *Proceedings of the Symposium on Adaptive Antennas.*, July 1980.**

**Kramer, J. D. R., Jr., "Adaptive Antenna Array Processing: A Study of Weight Error Effects," *International Specialist Seminar on Case Studies in Advanced Signal Processing IEE Conference Publication, No. 180*, September 1979.**



**David Lamensdorf  
Division D080**

**Education**

**Ph.D., Applied Physics, Harvard University, 1968**

Thesis topic: *An Investigation of Dielectric Coated Antennas*,  
**S.M., Applied Physics, electromagnetics, Harvard University, 1961**  
**B.E.E., Electrical Engineering, Cornell University, 1960**

**Employment History**

**1985 – Present: The MITRE Corporation, Bedford, MA**

**1983 – 1985: Sperry Defense Electronics, Waltham, MA**

**1967 – 1983: Sperry Research Center, Sudbury, MA**

**1972 – 1973: University College London, London, UK (one year leave from Sperry Research Center)**

**Work Experience**

**1985 – Present: The MITRE Corporation**

Since joining MITRE, Dr. Lamensdorf has been working in the Sensor Center on technology development and evaluation for new radar systems. During 1985–1986, he was an individual contributor as a lead engineer. Thereafter, he has been a group leader. The following are brief descriptions of his major tasks and accomplishments.

Beginning in FY92 and continuing through FY93, he has been the principal investigator for a Mission Oriented Investigation and Experimentation (MOIE) project on *Advanced Adaptive Arrays for Radar*. He has been directing a team of six people in the development of adaptive space-time processing techniques for the suppression of near field scattering and jammer multipath effects.

He participated in the development of plans for testing an advanced airborne radar system on a mountain top test range. This led to a white paper for the Air Force that outlined the critical issues and test objectives for this test program.

He formulated an approach and directed the development of a motion emulation technique that applies the appropriate Doppler frequency spread to clutter data measured with a stationary radar so that this data appears as if the radar is moving. This type of emulation is necessary for the effective use of the mountain top test range with an airborne radar.

He participated in MITRE's study of impulse radar that defined its potential performance capability and limitations for air surveillance. As part of this study, he performed a sensitivity analysis for this type of radar that became a significant part of the DARPA study on impulse radar.

He participated in MITRE's evaluation of contractors' proposed designs and technology studies for new airborne surveillance radars under the Airborne Surveillance and Technology Testing (ASTT) program.

For two years, he directed four people in a special project that studied *Adaptive Array Vulnerability*.

He directed several CORE project activities that are developing tools for the evaluation of radar systems. For several years he led a project that evaluated and implemented computer codes to predict the radar cross section of targets. Recently he has been directing a multiyear program to develop a signal prediction capability to be used for the evaluation of target identification techniques for helicopters.

#### **1983 – 1985: Sperry Defense Electronics, Senior Research Section Head**

Dr. Lamensdorf directed research and development work on multiple beam antennas, microwave module design for phased array antennas, and antenna site multipath modeling. These were done for several radar development programs that were then being done by Sperry.

#### **1967 – 1983: Sperry Research Center, Member of Technical Staff**

Dr. Lamensdorf was a principal investigator in applied research on electromagnetic problems, particularly as related to antennas and microwave technology. He conducted many research programs that involved analytical modeling and experimental verification. These included designing a leaky wave subarray antenna for a flat plate, millimeter wave array; developing a high scan rate antenna to suppress sea clutter for a marine radar based upon a transreflector; creating an analytical model for the dome antenna, a passive lens that enables a phased array radar to have a field of view that exceeds a hemisphere; and developing designs for the components of the lens and the feed array of the dome antenna. Over that period, particularly during the first five years, he worked on many projects that developed and applied short pulse technology (antennas, generators, and receivers) for subnanosecond pulse (impulse) radars, communications and measurement systems, and analyzed the time domain response of antennas. He also was a consultant with many divisions of the Sperry Corporation.

#### **1972 – 1973: University College London, Research Associate**

Dr. Lamensdorf worked on several research projects at the university while on a leave of absence for one year. He developed and demonstrated a method for broadband tuning of dipole antennas using capacitors and varactors, and he created a new microwave filter based upon the Rotman lens. He also assisted in the direction of several graduate students, advising them on their thesis projects.

#### **Teaching Experience**

**June 1988: Instructor for short course at IEEE AP-S/URSI Symposium, "Time Domain Electromagnetic Measurements," Syracuse, NY.**

**1987 – 1991: Adjunct Professor of Electrical Engineering, Northeastern University: thesis advisor to Ph.D. candidate.**

**1966 – 1967: Lecturer in Mathematics, Graduate School of Arts and Sciences, Northeastern University: taught a course on differential equations.**

#### **Hardware and Equipment**

**RF and microwave test and measurement equipment, Macintosh**

## **Professional Society or Association Memberships**

### **IEEE – Senior Member**

**Antenna and Propagation Society**

**Aerospace and Electronics Society**

**Social Implications of Technology Society**

### **URSI – commissions A and B**

**Eta Kappa Nu**

**Sigma Xi**

## **Foreign Languages**

**French (reading)**

## **Patents**

### **Issued**

**USA, Balanced Radiator, 3,659,203**

**USA, Transmission Line Presence Sensor, 3,750,125**

**USA, Transmission Line Presence Sensor, 3,801,976**

**USA, Borehole Telemetry System, 4,023,136**

**USA, Transreflector Scanning Antenna, 4,214,248**

### **Pending Under Secrecy Orders**

**High Scan Rate Low Sidelobe Circular Scanning Antennas**

**Antennas for Wide Bandwidth Signals**

**Low Radar Cross Section (RCS) High Gain Lens Antenna**

## **Total Journal and Conference Publications: 20**

### **Journal or Conference Publications Relating to Adaptive Processing**

**Barile, E. C., Guella, T. P., Lamensdorf, D., "Adaptive Antenna Space-Time Processing Techniques to Suppress Platform Scattered Clutter for Airborne Radar," accepted for publication in *IEEE Transactions on Aerospace and Electronic Systems***

**Barile, E. C., Guella, T. P., Lamensdorf, D., "Adaptive Antenna Space-Time Processing Techniques to Suppress Platform Scattered Clutter for Airborne Radar," 1993 *Antenna Applications Symposium*, Allerton Park, Monticello, IL**



**B. N. Suresh Babu  
Division D080**

**Education**

**Ph.D., Electrical Engineering, Oklahoma State University, 1978  
M.S., Electrical Engineering, Bangalore University, India, 1971  
B.S., Electrical Engineering, Bangalore University, India, 1969**

**Employment History**

**1989 – Present: The MITRE Corporation, Bedford, MA, Lead Engineer  
1979 – 1989: The MITRE Corporation, Bedford, MA, Member of Technical Staff  
1978 – 1979: Magnetic Peripherals, Inc., Oklahoma City, OK, Electronics Engineer  
1974 – 1978: Oklahoma State University, Stillwater, OK, Graduate Teaching Assistant  
Summer 1975: Rockwell International, Collins Radio, Dallas, TX, Engineer/Scientist  
1971 – 1974: New Government Electric Factory, India, Research & Development Engineer**

**Work Experience**

**1979 – Present: The MITRE Corporation**

**Dr. Suresh Babu is a lead engineer in the Advanced Radar Technology Department of the D080 Surveillance Division. He joined MITRE in 1979 and was promoted to Lead Engineer in 1989. Dr. Suresh Babu's expertise is in surveillance radar systems, phased arrays, radar signal processing, and antenna and transmitter systems. He is currently leading a project to develop new test methods for analog-to-digital (A/D) converters. The focus of the study is on predicting the impact of nonlinearities in clutter and jamming environments.**

**Atmospheric Surveillance and Tracking Technology (ASTT) —** Dr. Suresh Babu was a leading contributor to the ASTT program providing major contributions in several key technology areas. He assisted in evaluating airborne radar designs offered by three contractors. He concentrated in assessing the capabilities and limitations of Space-Time Adaptive Processing (STAP) for enhanced clutter suppression. Under this effort he developed a new low noise A/D converter architecture (16/18-bit resolution, 10 MHz) which advanced the technology. Dr. Suresh Babu also supported the DARPA system integration and testing carried out for Rome Laboratory (RL). Under the DARPA effort he supported the initial design evaluation for the L-band radar.

**Advanced Airborne Radar Simulation —** Dr. Suresh Babu led a test to develop an advanced airborne radar simulation for evaluation of STAP antenna techniques. The simulation is an end-to-end simulation which includes aircraft interaction effects, space-time-processing, and system performance.

**North Warning System —** He was the principal investigator in the evaluation of alternative A/D converters for the North Warning System.

**A/D Converter Effects on Airborne Radars —** He investigated/analyzed "A/D Converter Effects on Airborne Radars" on a special MITRE Division D080 project. The study included both analytical and hardware investigations of the causes and effects of intermods and nonlinearities caused by A/D converters. The results of the study are applicable to planned AWACS E-3 improvements.

North Warning System (NWS) — He analyzed antenna pattern characteristics of a cylindrical array being developed for use on the NWS. He developed a simulation model and algorithms for generating correlated Weibull variates.

Berlin Radar Program — He monitored the contractor's effort to modify the UNIX operating system for operation in a real-time air traffic control application. He initiated a study of the performance of several target tracking algorithms for the advanced tactical radar.

Scope Shield and Enhanced JTIDS — He studied the utility of a digital speech technique known as LPC-10 for the Enhanced JTIDS system and two-way hand-held radios used by the Air Force Security police. He performed experiments using a variety of speech and background noise inputs and outlined a field test program to obtain additional data for evaluation of the LPC.

Anti-Jam Communication Techniques — He developed speech analysis and synthesis for anti-jam communications. He investigated and demonstrated performance of Multiple-Data-Rate Encoders for optimizing Speech Quality over a range of jamming levels in quiet and noisy E-4A aircraft environments.

Narrow-Band Secure Voice Communication — He conducted research in narrow-band speech coding and robust speech processing in acoustic background noise. He developed 2400 BPS voice coding techniques based on the use of the fast Fourier transform, and developed vector quantization software for low data-rate digital voice communication.

MX Trajectory Analysis — He performed trajectory analysis and analyzed the footprint performance of the MX and trident missiles.

1978 - 1979: Magnetic Peripherals, Inc., Oklahoma City, OK, Electronics Engineer

He worked on modeling, design, and analysis of magnetic systems; digital hardware design, and development of read/write circuitry for data recovery.

1974 - 1978: Oklahoma State University, Stillwater, OK, Graduate Teaching Assistant

He conducted research in digital filtering and digital signal processing. He taught laboratory courses and assisted in teaching several graduate and undergraduate courses.

1971 - 1974: New Government Electric Factory, Bangalore, India, Research and Development Engineer

He worked on the application of nonlinear programming to induction motor designs, development of cut-through test apparatus for measuring the softening temperature of enameled wire, and heat transfer studies in induction motors.

### Teaching Experience

Dr. Suresh Babu taught one semester of Digital Communication Systems for the Department of Systems and Computer Engineering at Boston University (September 1980). In addition, he has taught several graduate courses in the areas of linear and non-linear control theory, optimal control systems, digital signal and speech processing, digital filters, and probability theory. He also taught an undergraduate course in Electronic Circuits for the Department of Electrical Engineering at Northeastern University (1984). He was an invited guest speaker on Adaptive Arrays/Adaptive Signal Processing Lecture Series organized by the IEEE. He presented a tutorial course on "Adaptive Processing for Speech," at the Museum of our National Heritage, Lexington, MA, 18 November 1982.

## **Hardware and Equipment**

**IBM PCs, IBM mainframes, VAX, VMS systems, PDP-11 and Cyber**

## **Software**

***Operating Systems:* PC DOS and UNIX**

***Programming Languages:* FORTRAN, PASCAL, ALGOL and C**

***Applications:* MS Word**

***Teleprocessing Monitors and Environments:* MS Windows**

## **Professional Society or Association Memberships**

**Senior Member IEEE**

**Chairman of the IEEE Boston Chapter on ASSP 1987-1988**

**Vice Chairman of the IEEE Boston Chapter on ASSP 1986-1987**

**Secretary of the IEEE Boston Chapter on ASSP 1985-1986**

## **Professional Honors**

Received a letter of appreciation from the President and CEO of MITRE along with a cash award for the invention of a "High-Speed High Resolution A/D Converter Subranging Architecture," 23 December 1991

MITRE Program Achievement Award for contributions made to the definition, development, testing and operational evaluation of the AN/FPS-124 Unattended Radar of the North Warning System, June 1990

MITRE Initiative Awards, 1984, 1987, and 1992

MITRE Best Paper Award for "Performance of an FFT Voice Coding System in Quiet and Noisy Environments," published in an IEEE Journal, 1983

National Merit Scholarship, Government of India, 1965

## **Foreign Languages**

German, Kannada, Hindi, Sanskrit, Tamil

## **Patents**

"High-Speed High Resolution A/D Converter Subranging Architecture" United States Patent, patent 5248973, 28 September 1993

## **Total Number of Journal and Conference Publications: 18**

### **Journal or Conference Publications Relating to Adaptive Processing**

Suresh Babu, B. N., Torres, J. A., "Adaptive Airborne Radar Simulation with Equalization Filter Taps," *Summer Computer Simulation Conference*, Boston, MA, 1993.

Suresh Babu, B. N., Torres, J. A., "Airborne Radar Simulation with Adaptive Antenna Techniques," *Summer Computer Simulation Conference*, Reno, NV, July 1992.



**Jose A. Torres  
Division D080**

**Education**

**Ph.D. Candidate, Electrical Engineering, concentration in Signal Processing, Northeastern University**  
**M.S., Electrical Engineering, concentration in Signal Processing, Northeastern University, 1989**  
**B.S., Electrical Engineering, Rensselaer Polytechnic Institute, 1984**

**Employment History**

**1986 – Present: The MITRE Corporation, Bedford, MA**  
**1984 – 1986: Westinghouse Electric Corporation, Monroeville, PA**

**Work Experience**

**1986 - Present: The MITRE Corporation, Bedford, MA**

Mr. Torres has supported efforts to design and develop advanced adaptive signal processing algorithms and architectures that improve the detection performance of future radar systems. Early assignments were in support of a frequency domain signal processor for a wideband high-frequency over-the-horizon radar. This involved development of functional and bit level simulations, and theoretical performance prediction analyses of the programmable length FFT and narrowband interference suppression subsystems. For the last several years, the adaptive processing work has focused on airborne surveillance radars. Completed and ongoing studies have addressed the optimal adaptive cancellation of Doppler-spread clutter, near-field scattering effects, and jammer multipath. Development of adaptive suboptimal transform domain techniques to reduce the complexity of the optimal processing algorithms are ongoing.

**1984 – 1986: Westinghouse Electric Corporation, Monroeville, PA**

Mr. Torres was a systems engineer supporting nuclear-naval programs. He supported the development and modification of microprocessor-based subsystems that monitor the operational status of nuclear powered submarines. This involved development of system hardware and software specifications, test plans, installation procedures, and maintenance requirements.

**Hardware/Equipment**

**Sun workstations, Macintosh, DEC VAX, CRAY**

**Software:**

***Operating Systems:* UNIX, MacOS, VMS**

***Programming Languages:* FORTRAN, C**

***Applications:* MATLAB, Word, TEXtures, MacDraw Pro, PowerPoint**

## **Professional Honors**

**Recipient of MITRE Best Paper Award, 1993**

## **Foreign Languages**

**Spanish**

**Total Journal and Conference Publications : 7**

### **Journal or Conference Publications Relating to Adaptive Processing**

**Fante, R. L., Torres, J. A., "Cancellation of Diffuse Jammer Multipath by an Airborne Adaptive Radar," accepted for publication in the *IEEE Trans. on Aerospace and Electronic Systems*, 1994.**

**Fante, R. L., DiPietro, R. C., Torres, J. A., "Cancellation of Diffuse Jammer Multipath—Suboptimum Frequency Space Processing," submitted to *IEEE Trans. on Aerospace and Electronic Systems*, 1994.**

**Suresh Babu, B. N., Torres, J. A., "Adaptive Airborne Radar Simulation with Equalization Filter Taps," *Proceedings of the 1993 Summer Computer Simulation Conference*, pp. 529–534, July 1993.**

**Barile, E. C., Fante, R. L., Guella, T. P., Torres, J. A., "Performance of Space-Time Adaptive Airborne Radar," *Record of the 1993 National Radar Conference*, pp. 173–175, April 1993.**

**Barile, E. C., Fante, R. L., Torres, J. A., "Some Limitations on the Effectiveness of Airborne Adaptive Radar," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 28, pp. 1015–1032, October 1992.**

**Suresh Babu, B. N., Torres, J. A., "Airborne Radar Simulation with Adaptive Antenna Techniques," *Proceedings of the 1992 Summer Computer Simulation Conference*, pp. 484–490, July 1992.**

**Barr, P. C., Torres, J. A., "Finite-Register Simulation for a Radar Signal Processor," *Proceedings of the 1990 Summer Computer Simulation Conference*, pp. 418–423, July 1990.**

**Ronald Thomas Williams**  
**Division D080**

**Education**

**Ph.D., Electrical Engineering, concentration in Signal Processing, The Pennsylvania State University, 1989**

**M.S., Electrical Engineering, concentration in Communication Theory, The Pennsylvania State University, 1984**

**B.E.E, Electrical Engineering, concentration in Signal Processing, University of Delaware, 1983**

**Employment History**

**1988 – Present: The MITRE Corporation, Bedford, MA**

**Work Experience**

**1988 – Present: The MITRE Corporation, Bedford, MA**

**Dr. Williams is a Group Leader in the Advanced Systems Department of the Surveillance Division. He joined MITRE in 1988 after completing the Ph.D. degree.**

**1988 – Present:** Since 1988 Dr. Williams has supported efforts to develop advanced adaptive array processing techniques for cancelling interference, atmospheric noise, and clutter in wide bandwidth high frequency (HF) radar and communication systems. In FY89 and FY90, Dr. Williams led a Mission Oriented Investigation and Experimentation (MOIE) project entitled Robust Adaptive Beamforming that developed and analyzed adaptive beamforming techniques. Through both theoretical analysis and experimentation using MITRE's Bedford and Forestport arrays, this project assessed the performance of a constrained Gram-Schmidt sidelobe cancellation algorithm. Dr. Williams also collaborated with two senior members of the signal processing department (D051) to develop and analyze a constrained principal components based algorithm that addressed many shortcoming of the conventional Gram-Schmidt based approach. Dr. Williams is currently supporting efforts to apply direction-of-arrival estimation and adaptive array processing techniques to data recorded at the MITRE Texas Facility. The goal of this work is to map the spatial spectra of atmospheric noise sources at HF and to determine the efficacy of using adaptive nulling techniques to reduce the background noise level.

**1991 – 1992:** As part of the MSR project, Probabilistic Data Association for Signal Sorting (91660), Dr. Williams lead efforts to apply the joint probabilistic data association (JPDA) algorithm, developed for use in multiple-target tracking applications, to associate hops from multiple frequency hop (FH) transmitters and to assess the performance of this approach using Monte Carlo simulation techniques. Accomplishing the technical objectives of the project required the development of dynamic statistical models for signal parameters used to describe the FH signals, interferers, and the false alarms. It also required that conventional tracking methods be adapted to the FH signal sorting problem. Finally, a significant part of our effort centered on the design and implementation of a large software test bed that will be used to assess the performance of candidate signal sorting algorithms. As a result of this work, we successfully developed a JPDA based signal sorting algorithm, demonstrated its ability to associate FH signal hops with their transmitters, and evaluated the performance of this algorithm through Monte Carlo simulations.

1990 – 1991: Dr. Williams supported the MSR project, Electronic Warfare Techniques (9141B), that has developed an electronic countermeasure called adaptive crosseye designed to counter antiaircraft missile threats. As part of this project, he analyzed the effects of array calibration errors on the performance of the adaptive crosseye algorithm. His work resulted in analytical expressions that predict the effects on system performance of both phase and amplitude errors in the crosseye sensors. The accuracy of this analysis was verified through computer simulation.

### **Teaching Experience**

Dr. Williams taught introductory level courses in digital system design and communication theory for the Electrical Engineering Department at the Pennsylvania State University, University Park, PA (fall 1983 through summer 1984).

### **Hardware/Equipment**

Sun workstations, Macintosh

### **Software**

*Operating Systems:* UNIX, VMS

*Programming Languages:* FORTRAN, C

### **Professional Society or Association Memberships**

Member of the IEEE

**Total Number of Journal or Conference Publications: 8**

### **Journal or Conference Publications Relating to Adaptive Processing**

Williams, R. T., Mahalanabis, A. K., Sibul, L. H., and Prasad, S., "An Efficient Signal Subspace Algorithm for Source Localization in Noise Fields with Unknown Covariance," *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing*, pp. 2829-2832, April 1988.

Williams, R. T., Prasad, S., Mahalanabis, A. K., and Sibul, L. H., "An Improved Spatial Smoothing Technique for Bearing Estimation in a Multipath Environment," *IEEE Transactions on Acoustics, Speech, and Signal Processing*, Vol. 36, pp. 425-432, April 1988.

Carhoun, D. O., Games, R. A., and Williams, R. T., "A Principal Components Sidelobe Cancellation Algorithm," *Conference Record of the Twenty-Fourth Asilomar Conference on Signals, Systems and Computers*, pp. 763-768, November 1990.

Games, R. A., and Williams, R. T., "Performance Analysis of a Concurrent Adaptive Least-Squares Sidelobe Cancellation System with Excess Degrees of Freedom," *Digest of the 1991 Antennas and Propagation Society Symposium*, pp. 86-89, June 1991.

Games, R. A., Townes, S. A., and Williams, R. T., "Experimental Results for Adaptive Sidelobe Cancellation Techniques Applied to an HF Array," *Conference Record of the Twenty-Fifth Asilomar Conference on Signals, Systems and Computers*, pp. 153-159, November 1991.

## **Section 4**

### **Reprints of Four Selected MITRE Papers Relating to Adaptive Processing**



# PERFORMANCE OF SPACE-TIME ADAPTIVE AIRBORNE RADAR

Edward C. Barile  
 Ronald L. Fante  
 Thomas P. Guella  
 Jose A. Torres  
 The MITRE Corporation  
 Bedford, MA 01730

## ABSTRACT

In this paper we study how internal clutter motion, channel mismatch, platform interaction and non-stationary jammer multipath limit the effectiveness of an airborne adaptive radar. Approaches to mitigate these effects are discussed.

Unlike a ground-based radar, in which all of the clutter is received at or near zero-Doppler, the clutter return in an airborne radar has Doppler frequencies spread over a band of width  $4V/\lambda$ , where  $V$  is the platform speed and  $\lambda$  is the radar wavelength. Therefore, conventional moving target indicator (MTI) is ineffective in cancelling clutter without also cancelling desired targets. Another feature of airborne radar is that there is usually clutter in the same Doppler cell as a target, but it usually arrives from a different azimuth, as illustrated in figure 1 for the case of frozen clutter (i.e., no internal motion). This suggests that adding spatial degrees of freedom to the conventionally-used temporal degrees of freedom should allow us to place a null along the azimuth of the clutter that competes with the target, thus allowing the clutter to be cancelled, without cancelling the desired target return. In constructing figure 1 we assumed that the pulse repetition rate is such that there are no range or Doppler ambiguities. A typical space-time processor that combines spatial and temporal degrees of freedom is shown in figure 2. The processor is formed by placing a tapped delay line at the output of each of  $L$  antennas of the array, with the taps spaced by one pulse repetition interval (PRI). This processor constitutes the number of antenna elements times the number of PRI taps (i.e., pulses) degrees of freedom.

The adaptive weights in the processor shown in figure 2 are chosen to maximize the signal-to-noise-plus-clutter-plus-jammer ratio  $S/(N + C + J)$  for a specified desired signal (i.e., specified azimuth and Doppler). It is found that  $S/(N + C + J)$  is maximized if the weight vector  $w = [w_{11} \ w_{21} \ \dots \ w_{L1} \ w_{12} \ \dots \ w_{L2} \ \dots]^T$  is given by [1]

$$w = \mu M^{-1} s^*, \quad (1)$$

where  $\mu$  is a constant,  $M$  is the covariance matrix defined as  $M = \langle U U^* \rangle$ ,  $\langle \rangle$  denotes an expectation,  $U$  is the received voltage vector given by

$$U = [U_1(t) \ \dots \ U_L(t) \ \ U_1(t-T) \ \dots \ U_L(t-T) \ \dots]^T,$$

and  $s$  is the steering vector that describes the voltage that would be received on the array if a target at the desired azimuth and with the desired Doppler were present. In the above equations the superscript  $T$  denotes a transpose,  $*$  denotes complex conjugate and  $+$  denotes conjugate transpose. When  $w$  is given by equation (1) it can be shown [1] that  $S/(N + C + J)$  after adaptation is given by

$$\frac{S}{N + C + J} = s^T M^{-1} s^*. \quad (2)$$

In an ideal world in which all clutter is frozen, channel match is perfect, jammers are narrow band and have no multipath from the earth, and platform-antenna interactions are negligible, etc., it can be shown that

$$\frac{S}{N + C + J} \rightarrow \frac{|s|^2}{\sigma^2}, \quad (3)$$

where  $\sigma^2$  is the noise power. Thus, under ideal conditions the adaptive airborne processor shown in figure 2 can completely cancel all clutter and interference. In reality, the radar must also cope with the effects of internal clutter motion, platform crabbing, channel mismatch and other errors, finite jammer bandwidth, jammer multipath (also known as "hot clutter") and antenna - platform interactions.

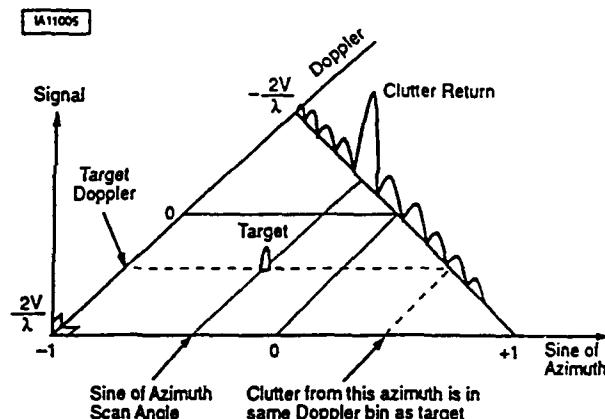


Figure 1. Clutter Return in Doppler-Azimuth Space

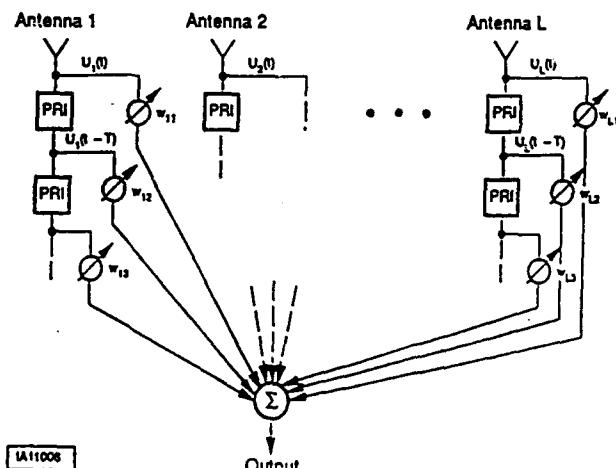


Figure 2. Generalized Space-Time Processor

In this paper, we quantitatively discuss how each of the aforementioned factors limits radar performance. For example, internal clutter motion limits performance by spreading the clutter off the frozen clutter line in figure 1 and gives the loss in performance shown in figure 3. It is seen that this performance loss is best compensated for by processing more pulses (i.e., temporal degrees of freedom), as opposed to adding more spatial degrees of freedom (i.e., antenna elements).

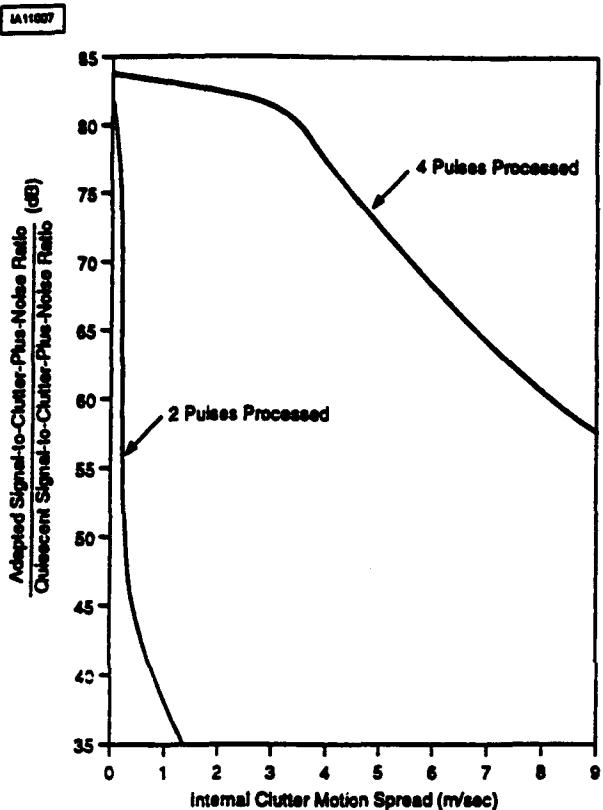


Figure 3. Effect of Internal Clutter Motion on the Performance of a 50 Element Array that Processes 2 and 4 Pulses. The Quiescent Signal-to-Clutter-Plus-Noise Ratio is -55.1 dB

Channel mismatch is another important consideration, since it determines the processor's ability to provide adequate nulling of jammers and clutter. The effect of channel mismatch on the nulling of clutter is shown in figure 4. Performance loss can be mitigated by tightly controlling dispersive antenna errors, and to a lesser extent, by increasing the number of spatial degrees of freedom, as shown in figure 4.

Antenna-platform interaction can present a serious limitation on performance because near-field obstacles destroy the unique azimuth-Doppler relationship of the clutter return. A geometrical theory of diffraction code (NECBSC) has been used to model antenna-aircraft interactions. A typical result at 435 MHz for an aircraft-mounted billboard antenna is shown in figure 5. Note that the presence of the near-field obstacle (i.e., aircraft wings, etc.) requires the use of significantly more degrees of freedom to achieve a given improvement than are required when the aircraft structure is absent.

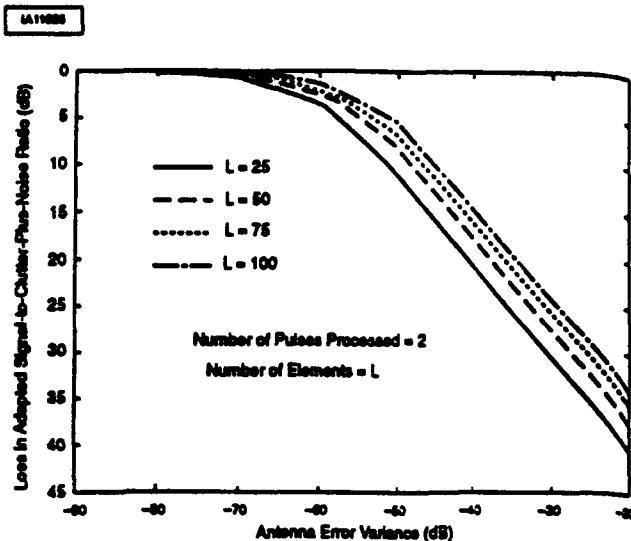


Figure 4. Effect of Channel Mismatch on the Performance of an L-Element Array. The Quiescent Noise-to-Clutter Ratio was Approximately -85 dB for  $L = 25$ , -88 dB for  $L = 50$ , -90 dB for  $L = 75$  and -92 dB for  $L = 100$ .

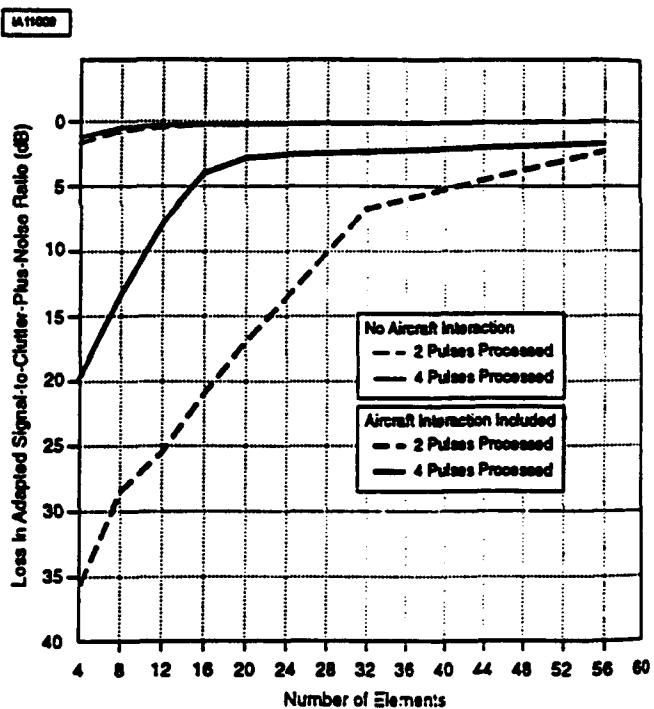


Figure 5. Effect of Antenna-Platform Interaction on Performance of an Aircraft Mounted Array at 435 MHz

In the absence of multipath, jammer cancellation is limited primarily by channel mismatch. However, when multipath is included it brings about some rather unusual effects because both the radar platform and the jammer are in motion. In order to illustrate this, suppose a narrowband jammer is present. Then, over some terrains large Doppler beats may exist between the direct jammer signal and the multipath from different specular regions, such as hills, TV towers, etc. This causes the covariance matrix  $M$  to

become temporally nonstationary, and it then needs to be either temporally or spatially smoothed (by subaperture averaging) to remove this non-stationarity, or the weights must be updated at a rate that is faster than the highest Doppler beat present. In figure 6, we show the loss in performance versus time when a narrowband sidelobe jammer is at azimuth  $\phi = 70^\circ$ , four specular reflections are at  $\phi = 62^\circ, 52^\circ, 42^\circ$ , and  $-80^\circ$ , and there is no clutter or diffuse multipath. (The diffuse multipath contributes a term to the covariance that is clutter-like, except that it has a different Doppler structure). In the first case, a full 40-element aperture is used with the weight vector calculated at  $t = 0$  applied for all later time; but in the other case 11, 30-element subapertures are spatially averaged to form a smoothed covariance matrix  $\bar{M}$ , and the weight  $\bar{W} = \bar{M}^{-1} \bar{s}^*$  is then applied. Note that spatial smoothing dramatically improves the performance, as long as there are no strong near-field obstacles present, because they degrade the effectiveness of spatial smoothing in decorrelating the reflections, as shown by the corresponding curve in figure 6. It should be emphasized that the improvement shown in figure 6 (for no near-field obstacle) is no longer achieved if the primary jammer interference or any of the reflections enter through the antenna mainbeam. In that case, the performance achieved by subaperture averaging is significantly degraded (by nearly 40 dB for the configuration chosen in figure 6, with the reflection at  $-80^\circ$  moved to  $\phi = 1^\circ$ ). Therefore, sub-PRI tapped delay lines (i.e., taps spaced by less than the reciprocal of the jammer bandwidth) [2,3] or interferometric approaches are then required for additional improvement.

The other option, of course, is to update the weights at intervals  $\Delta t \ll f_d^{-1}$  where  $f_d$  is the highest Doppler beat. In that case it is found that because the narrowband direct and specularly reflected jammer signals are then all correlated, the covariance matrix has only a single dominant eigenvalue (for  $P$  direct jammers there are up to  $P$  eigenvalues that are large in comparison with the noise), and nearly complete cancellation of the jammer and its specular reflections is possible, even if the jammer lies within the mainbeam. This is readily seen by re-expressing equation (2) in terms of the eigenvalue  $\lambda_1$ , and the eigenvectors,  $e_k$ , of  $M$ . We then have for  $K$  degrees of freedom [4]

$$\frac{S}{N+J} = \frac{|s^T e_1|^2}{\lambda_1 + \sigma^2} + \sum_{k=2}^K \frac{|s^T e_k|^2}{\sigma^2}, \quad (4)$$

where  $\sigma^2$  is the noise variance. Because  $\lambda_1 \gg \sigma^2$ , for a single narrowband direct jammer and its specular reflections, we then have (neglecting a term of order  $1/K$ , which is small for  $K \gg 1$ )

$$\frac{S}{N+J} = \sum_{k=2}^K \frac{|s^T e_k|^2}{\sigma^2} = \frac{1}{\sigma^2} \sum_{k=1}^K |s^T e_k|^2 = \frac{S}{N}. \quad (5)$$

Thus, the full signal-to-noise ratio in the absence of any jamming is recovered (to within a factor of order  $1/K \ll 1$ ).

In the limit when the jammer is wideband, a very different situation occurs, and the multipath from both discrete and diffuse scatterers add incoherently in a fashion that is similar to noise. However, unlike noise, these multipath components will exhibit some correlation from antenna element to element.

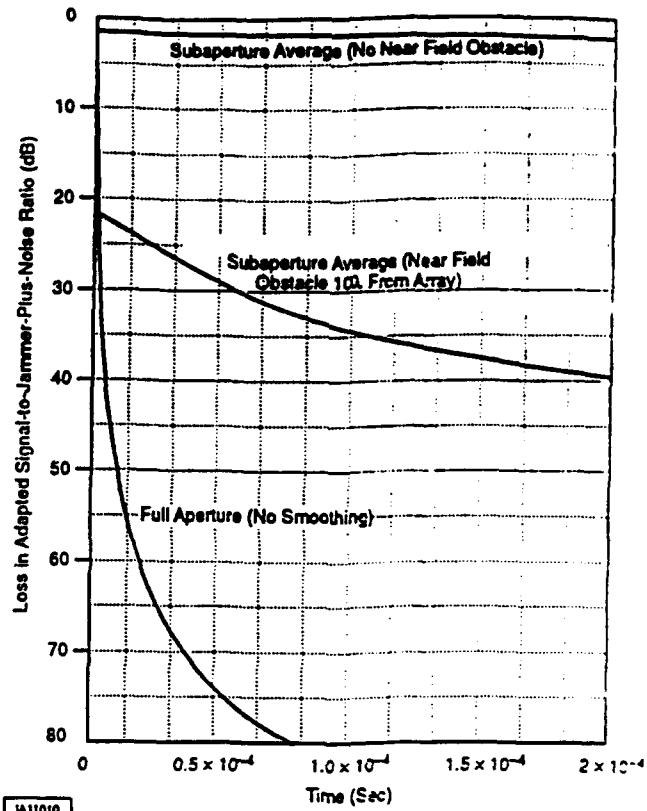


Figure 6. Loss in Performance for a Forty-Element Array that Uses Eleven, Thirty-Element Subapertures for Smoothing When the Array is Illuminated by a Jammer at  $\phi = 70^\circ$  Plus Reflections at  $\phi = 62^\circ, 52^\circ, 42^\circ, -80^\circ$

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# HIGH FREQUENCY ATMOSPHERIC NOISE MITIGATION

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## ABSTRACT

*The performance of high frequency (HF) radio communication and radar systems can be limited by noise generated by sources external to the receiving antenna. Below 10 MHz, atmospheric noise generated by worldwide thunderstorm activity tends to be the dominant natural source. In this paper we present an empirical analysis of atmospheric noise cancellation achieved by applying an adaptive sidelobe canceller to wideband HF signals measured using the MITRE Texas Facility. We couple our empirical analysis with predicted results obtained using CCIR noise models to assess the likelihood of obtaining significant levels of noise cancellation. We also describe cancellation performance as a function of the degrees of freedom applied and variations in adaptation rate.*

## INTRODUCTION

The high-frequency (HF) band (3-30 MHz) is a useful medium for a variety of communications and surveillance applications for which over-the-horizon propagation is essential. Signals transmitted at HF have the unique ability to propagate great distances beyond the line-of-sight of the transmitter through refraction by the ionosphere. In exchange, the HF user must cope with the vagaries of ionospheric propagation and other phenomena unique to the HF medium. One of these is the ambient atmospheric noise generated by electrical discharges within thunderstorms and propagated around the world. The ambient atmospheric noise, which often limits system performance, has unique spatial and temporal characteristics that can be exploited to minimize its deleterious effects on signal detection and estimation. Unlike other HF noise sources that have a nearly isotropic spatial distribution, atmospheric noise is likely to be confined to a narrow spatial sector. Consequently, it is susceptible to being cancelled by various spatial filtering techniques. The possibility of mitigating the ambient atmospheric noise makes HF a more attractive solution for many critical applications.

### Ambient Noise

Ambient noise in the HF band consists of atmospheric, galactic, and man-made components. The atmospheric noise power spectrum drops rapidly with

frequency. Propagation at low frequencies is most favorable in the hours after dark when D-layer absorption is absent. Consequently, atmospheric noise in the HF band is dominant at night and below 10-15 MHz.

The atmospheric noise component arises from the discharge of meteorologically generated electric charge. The relationship between atmospheric noise and lightning has been known for many years. Atmospheric noise at HF arises from nearby storms and, by ionospheric propagation, from storms around the world. The worldwide distribution of lightning has been observed from ground stations and by satellites using optical or electromagnetic sensors. These studies (see, for example, [5]) demonstrate that atmospheric noise has directional properties determined by the worldwide distribution of thunderstorms and modified by ionospheric propagation. Our task is to investigate these properties and to show how these directional characteristics can be exploited to mitigate the atmospheric noise.

### Wide Bandwidth Data Collection

The analysis work described in this paper is based upon data collected using MITRE's HF research facility. The MITRE Texas Facility (MTF) is located on land owned by the University of Texas System approximately 60 miles southwest of Odessa, Texas. This rural location is largely free of major man-made noise sources. The MTF consists of a planar array of monopole antenna elements whose outputs feed a series of tunable wide bandwidth receivers. The facility provides a unique capability to collect short segments of digitized wide bandwidth data for later off-line analysis. Longer segments of data can be recorded provided the bandwidth is reduced. Since the facility consists of a planar array, the MTF provides both azimuth and elevation directivity.

The antenna array consists of 96 vertical monopoles located within a 3 kilometer diameter circle. The locations of the antennas have been selected randomly with a 239-meter minimum distance to neighboring antennas. The monopole elements are triangular tower sections 20 feet (6.3 meters) high and 16 3/4 inches on a side. The large size of the tower and the 16 40-foot radials buried 6 inches deep combine to give the monopole favorable electrical properties over the entire 4-30 MHz operating band. Groups of 32 antenna elements are linked to electronic

equipment in shelters called nodes. Data from the monopole antennas form the input to wide bandwidth receivers located in the shelters.

Each node shelter houses 32 wide bandwidth digitizing receivers and recorders. The receivers have a nominal 1.024 MHz bandwidth which can be located anywhere in the 4 to 30 MHz HF band. Each receiver digitizes a selected 1.024 MHz bandwidth and outputs 16-bit in-phase and quadrature (I and Q) data at a 2.048 MHz rate. The center frequency and analog gain of the receivers are under digital control. The data recorder has eight megabytes of random access memory (RAM) per receiver channel, providing slightly more than 1 second of continuous data recording. Once the RAM is filled, the contents are transferred to 8 millimeter tape for off-line processing.

During 1993, the MITRE Texas Facility was used to record wide bandwidth data believed to contain atmospheric noise. The recordings were conducted from 25-28 January, 29 March through 2 April, and 21-25 June. During these time periods, data was typically recorded from 6 p.m. until 3 a.m. Central Standard Time (CST) at frequencies ranging from 4.5 to 15 MHz. The collection schedule and frequency range were chosen to maximize the likelihood of recording atmospheric noise. Power spectrum estimation techniques were used to identify data sets likely to contain strong atmospheric noise.

#### Adaptive Antenna Processing

It has been known since the early days of radio that atmospheric noise can be reduced by a directional antenna. More recently the use of spatial adaptive processing to mitigate this noise has been considered. Griffiths [4], working with the Wide Aperture HF Radio Research Facility, showed improvements in signal-to-noise ratio of 10-15 dB using adaptive processing. However, his work did not distinguish between atmospheric noise and other forms of interference. In the subsequent discussion we consider the problem of explicitly minimizing atmospheric noise using adaptive array processing techniques.

To demonstrate cancellation of atmospheric noise, we applied a concurrent block-processing-based sidelobe canceller to elemental data from the MTF. The sidelobe canceller adaptively computes a set of antenna weights that minimize the output power of the array over a specified data block. The data samples used to train the adaptive weights were obtained from the same block to which the weights were later applied. The sidelobe canceller is composed of a primary element and a set of auxiliary antennas. The outputs of the auxiliary antennas are adaptively weighted and combined to form a single output. The combined samples are then subtracted from the primary element to produce the sidelobe canceller output or residual.

The optimization process used to compute the residual output minimized the array output power over a specified data block. The adapted weights were determined by solving a well-known least-squares problem. In the subsequent development we formulate the underlying least-squares problem that must be solved to compute the weights and present an overview of the implementation used to obtain the data analysis results. Our development assumes the signals and noise are narrowband. To apply the sidelobe canceller to wideband data collected at the MTF, subbanding techniques outlined in [2] were applied.

To begin, assume  $m$  samples are recorded from  $n$  auxiliary antenna elements and a single primary element. Let  $x$  be an  $m \times 1$  vector containing the primary element samples and let  $Y$  represent an  $m \times n$  matrix consisting of samples from the auxiliary array sensors. The  $i$ th column of  $Y$  contains the  $m$  samples measured by the  $i$ th antenna element. Finally, we let the  $n \times 1$  vector  $w$  contain the  $n$  auxiliary antenna weights. It follows then that the residual output,  $z$ , is  $z = x - Yw$ . An estimate of the array output power can be determined by properly scaling the 2-norm of the residual data vector. Consequently, the sidelobe canceller selects  $w$  to minimize the 2-norm of  $z$ , that is

$$\min \|x - Yw\|_2.$$

This least-squares problem has a well-known solution (see [3], page 139) resulting in a residual vector

$$z = [I - Y(Y^H Y)^{-1} Y^H]x$$

where  $I$  represents the identity matrix and the bracketed quantity is recognized to be the projection operator onto the orthogonal complement of the column space of the auxiliary array data matrix,  $Y$  (see [3], page 138).

Throughout much of the analysis work a common sidelobe canceller design was used to process the data sets. The sidelobe canceller used a single monopole, located near the center of the array, as the primary element. The auxiliary array was formed using 31 antennas surrounding the primary element. The FFT size used to subband the data was set at 1024. This value was selected since it provided FFT subband widths that met the narrowband limitations. Using this FFT size, we were able to insure that the block size used to train the auxiliary array weights in each frequency bin exceeded twice the number of antenna elements included in the adaptation process while providing a reasonable match to the duration of the observed impulsive events. In this case an independent adaptation was performed on data blocks corresponding to a time interval of 32 milliseconds (ms). Given that the data file recorded slightly over 1 second of data, we were able to conduct 32 independent adaptations per data file.

## NOISE CANCELLATION RESULTS

To measure noise cancellation we applied the standard sidelobe cancellation technique to a cross-section of the data files collected during the January, March, and June data collection campaigns. Our results demonstrate the feasibility of cancelling ambient noise at HF and quantify the amount of cancellation that can be achieved. In the remainder of this section, we summarize the analysis results obtained to date. We couple our empirical analysis with predicted results obtained using CCIR noise models [1] to assess the likelihood of obtaining significant levels of noise cancellation. The CCIR models provide a statistical description of atmospheric noise power as a function of frequency, season, and time of day. In this section we also describe variations in cancellation level as a function of the degrees of freedom applied and performance variations due to data block size.

### Cancellation Performance Summary

Figure 1 demonstrates the relationship between the level of noise cancellation observed and the strength of the background noise relative to the CCIR median value. This figure depicts the level of noise cancellation obtained as a function of the noise figure measured at the input to the primary element relative to the CCIR predicted median value. Each data point corresponds to a single 32 ms cancellation experiment. The data samples represent a cross-section of data collected in January, March, April, and June of 1993.

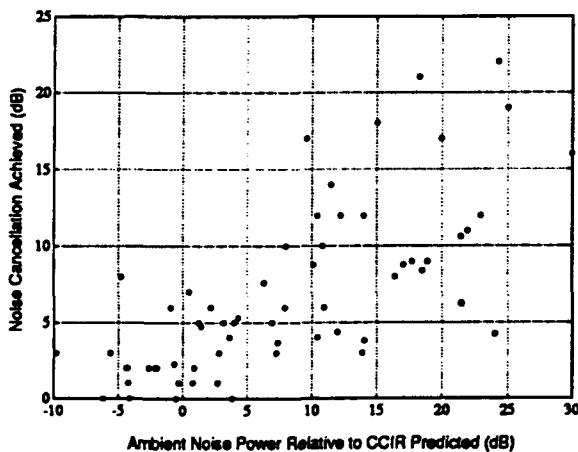


Figure 1. Noise Cancellation Versus Input Noise Level

A wide range of performance levels were obtained for the various data sets depicted in Figure 1. While cancellation levels between 20 dB and 30 dB were obtained in several data sets, noise reduction levels in the range of 3 dB and 10 dB were more common. As we would expect,

the amount of noise cancellation increased significantly as the input noise level rose above the CCIR median. However, when the noise level fell below the predicted median value, the level of noise cancellation was relatively low (less than 5 dB). It appears that the predicted CCIR median value provides a useful benchmark for predicting the level of atmospheric noise cancellation that can be achieved. The results suggest that the application of adaptive sidelobe cancellation techniques to HF data will provide significant benefit when the atmospheric noise level is the dominant noise source and its power exceeds the CCIR median value. The level of cancellation also appears to be closely tied to the CCIR median. As the noise level rises beyond the CCIR median value, a proportional rise in the noise cancellation level is observed.

### Cancellation Performance Versus Degrees of Freedom

An important objective of our analysis has been to evaluate atmospheric noise cancellation as a function of the available degrees of freedom. In analyzing data files containing significant levels of background noise, we found that substantial cancellation can often be obtained using fewer than five antenna elements. In some cases, we observed up to 10 dB of cancellation using a single auxiliary antenna. In general, however, sidelobe canceller performance varied significantly over time when the auxiliary array consisted of fewer than five antenna elements and often provided insignificant levels of cancellation when the number of auxiliary antenna elements was small. When five to ten elements were included, however, the sidelobe canceller consistently provided noise cancellation levels corresponding to more than half of the maximum achieved using the standard configuration of 31 auxiliaries. As the auxiliary array grew beyond ten elements, cancellation levels increased at a lower rate. Between 3 dB and 5 dB of additional noise cancellation was obtained by increasing the auxiliary array from 10 to 31 sensors.

Figure 2 shows typical cancellation results obtained for a varying number of adaptive antenna elements. These results were obtained by processing data file dc29234848, collected on 29 March at 16:48:48 CST at a frequency of 6.165 MHz, using the standard sidelobe canceller configuration with the number of auxiliaries varied from 1 to 31.

Figure 2 shows many of the features typically found in data files containing strong impulsive noise events. Early in the processing—generally, the first 448 msec of the file—up to 7 dB of noise cancellation was obtained using a single antenna element. An additional gain of 5 dB was obtained by increasing the number of auxiliaries to three. As the auxiliary array grew beyond three antennas, a gradual but steady increase occurred until a noise cancellation level of 20 dB was achieved. Note that for several data blocks, the noise figure for the residual exceeded the noise figure for the primary element when

one or sometimes two auxiliary antenna elements were used. This apparent rise in noise level was caused by leakage of strong narrowband interference into neighboring subbands and appears in the output due to the nonlinear nature of the sidelobe cancellation process. This effect is generally observed only when the background noise is weak.

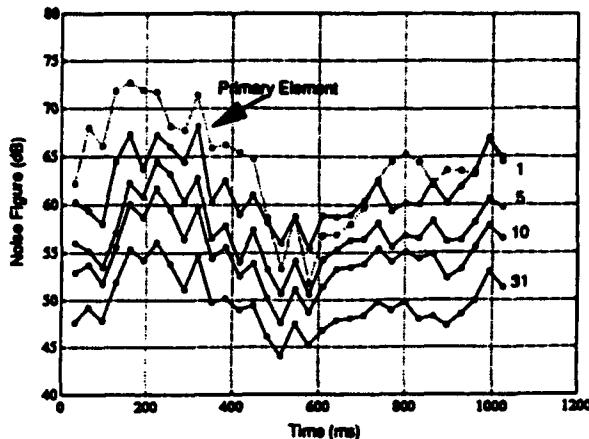


Figure 2. Noise Cancellation for Varying Numbers of Auxiliaries

#### Cancellation Performance Versus Block Size

Adaptive processing used to achieve noise cancellation will constitute only a single stage of a system's processing chain. It is often the case that other components of the system may place restrictions on or even precisely define the block length used during adaptive processing. For example, in OTH radar applications the block length may be required to match the dwell time of the radar to prevent undesired modulation of the signal and clutter. Increasing the block length used to train the adaptive weights has the effect of reducing the adaptation rate of the sidelobe canceller. Since atmospheric noise at HF is highly nonstationary, the effects of varying the block size on sidelobe canceller performance is a critical issue.

To perform this analysis, we designed an experiment in which the block size of the standard sidelobe canceller configuration described earlier was varied between 32 ms and 1024 ms. Our analysis results show that as the block length increased, the level of noise cancellation fell substantially. Figure 3 shows the cancellation results obtained for data file df24070500 collected on 24 June at 00:05:00 CST at a frequency of 7.8 MHz. Clearly, as the block size increased from 32 ms to 512 ms, the noise level found in the residual consistently increased by between 4 dB and 5 dB. Still, significant levels of cancellation were achieved using even the largest block size. For a block size of 512 ms, 5 dB or more of background noise cancellation was consistently achieved throughout the data file.

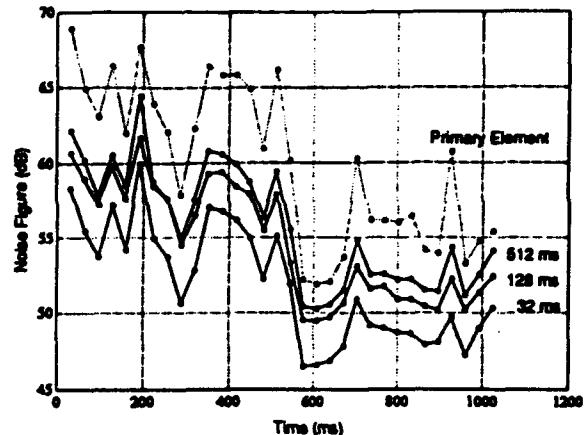


Figure 3. Noise Cancellation Versus Block Size

#### CONCLUSION

In this paper we presented an empirical analysis of atmospheric noise cancellation achieved by applying an adaptive sidelobe canceller to wideband HF data. Our results demonstrate typical noise cancellation levels ranging between 3 dB and 10 dB with peak levels exceeding 25 dB. Comparisons of cancellation results with CCIR noise models demonstrate that the CCIR median noise value provides a useful benchmark for predicting noise cancellation. During the course of our analysis, tradeoffs associated with the selection of the number of adaptive elements and the adaptation rate were also considered. Our results show that significant levels of cancellation can be achieved using between five and ten adaptive elements. In addition, our results quantify cancellation performance as a function of adaptation rate.

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# WIDE-BANDWIDTH HF NOISE MITIGATION USING A REAL-TIME ADAPTIVE SIDELOBE CANCELLER

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**ABSTRACT** Recent MITRE architecture and hardware efforts have culminated in the implementation of a real-time sidelobe canceller that has been integrated with the MITRE-Bedford 16-element receive array along with a processor that performs frequency domain subbanding. This paper describes how this experimental facility has been used to demonstrate the systematic real-time cancellation of noise bursts and narrow-bandwidth interference in the high frequency (HF) radio band. Powerful wide-bandwidth noise bursts can be reduced up to 20 dB by a subbanded sidelobe canceller with a single degree of freedom per subband.

## 1.0 INTRODUCTION

At times (particularly during winter nights in the lower parts of the 3-30 MHz HF band), it is postulated that the HF background noise level is determined by noise produced by worldwide thunderstorm activity. It is conceivable that these distant storms produce noise bursts of sufficient power and directivity that they can be cancelled using spatial filtering. If a noise burst is powerful enough to dominate the background noise or other narrow-bandwidth interferers, it can be cancelled by processing the data directly in the time domain. Often, though, there is a large number of narrow-bandwidth interferers that overwhelm the limited number of degrees of freedom available in a real-time system. In this case frequency domain subbanding can be employed, and the cancellation can be performed on narrower subbands. For subbands not containing a narrow-bandwidth interferer, the sidelobe canceller can now cancel the burst provided it is long and powerful enough to affect a sufficient number of FFT blocks involved in the subbanding. Narrow-bandwidth interferers contained in a subband will also be cancelled according to the number of degrees of freedom available.

Previous digital adaptive array processing at HF has been limited to the off-line analysis of recorded data. The narrow-bandwidth (780 Hz) Wide Aperture HF Radio Research Facility (WARF) has been used to show that both interference and background noise can be cancelled using

adaptive array processing techniques (Griffiths, 1976). Experiments with data recorded from an HF radar antenna array have demonstrated the ability to cancel impulsive noise in a 10 kHz bandwidth (Carhoun, 1990). Previous work involving off-line analysis of wide-bandwidth (1 MHz) data collected using the MITRE-Bedford 16-element array has shown that adaptive spatial filtering techniques can cancel HF burst noise and narrow-bandwidth interference while preserving a desired wide-bandwidth signal (Games, et al., 1991).

Recent MITRE architecture and hardware efforts have culminated in the implementation of a real-time sidelobe canceller (Rorabaugh, et al., 1991). The real-time sidelobe canceller is based on the Gram-Schmidt orthogonalization procedure (Golub and Van Loan, 1983, page 152) and uses concurrent block adaptation to derive an optimal residual directly from a block of data without explicitly computing the adaptive weights. Block lengths ranging between 32 and 128 are possible with the current implementation. At a block size of 128, the sidelobe canceller must complete a separate cancellation every 62.5 microseconds to maintain the 2.048 MHz throughput rate. For  $n$  auxiliaries, this requires on the order of  $16n^2$  million floating point operations per second.

The real-time sidelobe canceller has been integrated with the MITRE-Bedford 16-element array along with a processor that performs frequency domain subbanding.<sup>1</sup> This paper describes the experimental results obtained from applying this integrated testbed to reduce the interference found in the HF band. Although narrow-bandwidth interferers can be removed by a spatial filter, our emphasis is on the attenuation of wide-bandwidth noise sources over a 1 MHz band.

Section 2 describes the time-domain cancellation experiments. A plot showing the duration and structure of a representative burst of noise is included. A time-domain

<sup>1</sup> The authors acknowledge C. Beanland, G. Glatfelter, J. Manosh, L. Lau, K. Skey, and a host of others who have developed the HF array and the frequency domain processor.

real-time sidelobe canceller with a single auxiliary element attenuates these bursts up to 14 dB for narrow-bandwidths (10 kHz) and up to 10 dB for wide-bandwidths (1 MHz). Section 3 describes the frequency-domain experiments. A frequency-domain subbanded sidelobe cancellation configuration reduces the power of the multitude of narrow-bandwidth sources found in the HF band by amounts approaching 40 dB. Powerful wide-bandwidth noise bursts are reduced up to 20 dB in the frequency domain. A plot incorporating many minutes of data show the dramatic reduction in the variability of the noise floor achievable with spatial filtering.

## 2.0 TIME-DOMAIN SIDELOBE CANCELLATION EXPERIMENTS

Figure 1 shows the time-domain sidelobe cancellation configuration. Currently the real-time sidelobe canceller implements a single auxiliary. Also the primary channel corresponds to a single antenna of the MITRE HF array. The southwest array was used in all the experiments with the primary channel corresponding to antenna 16 and the auxiliary channel corresponding to antenna 14. Since the sidelobe canceller contained only a single degree of freedom, it was essential that the time-domain cancellation experiments be conducted on bands devoid of or containing only a few narrow-bandwidth interferers.

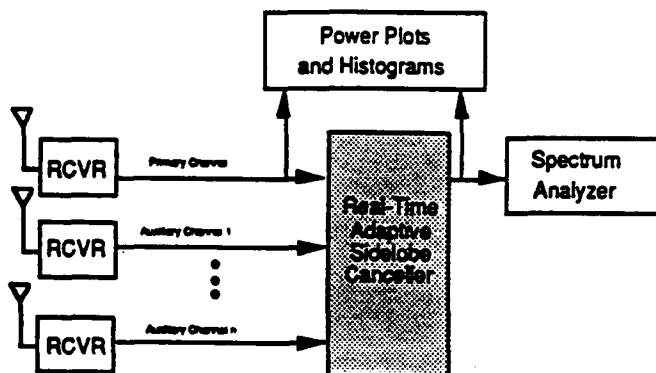


Figure 1. Time-Domain Sidelobe Cancellation Configuration

### 2.1 CANCELLATION OF LONG NOISE BURSTS

Bursts of wide-bandwidth noise of lengths ranging from tens of milliseconds to 1 second are common in data collected at the MITRE-Bedford facility. These long noise bursts could be caused, for example, by starting electrical motors.

Noise produced by lightning also appears to have a duration in this range. On the evening of 22 September 1992 a broad cold weather front beginning in Quebec, Canada, and extending through New York state, Pennsylvania, and down to eastern Texas passed across the eastern United States, replacing what had been a mass of hot and humid air. Thunderstorms accompanying the front were forecast. MITRE's southwest antenna array was well positioned to receive any wide-bandwidth noise bursts produced by these storms. A number of experiments designed to capture any noise bursts were conducted over a two and one-half hour period beginning at approximately 7:15 p.m. (EDT). During this time the front moved from eastern New York state into western Massachusetts. Sunset was at 6:42 p.m. (EDT).

The digital radios were tuned to a center frequency of 20.6 MHz. This band was selected to balance the need to keep the frequency low while at the same time limiting the number of narrow-bandwidth interferers present at the time of the experiment. The bandwidth of the radios was set at 10 kHz in an attempt to filter out the few narrow-bandwidth interferers that were observed in the 1 MHz band. To assess the levels of burst cancellation, a large number of short files were collected. The data was collected for as long as 16.384 seconds and as short as 1.024 seconds. Burst lengths between 400 and 800 milliseconds were typical. No precise statistical analysis was conducted on the frequency of these bursts, but they seemed to be averaging one event every one or two seconds. Figure 2 shows a representative file corresponding to 1.024 seconds of data. Peak cancellations of up to 14 dB are observable.

In a practical wide-bandwidth system, the burst activity will occur in combination with a significant amount of powerful narrow-bandwidth interference. This will make cancelling the bursts problematic in the time domain. A potentially more practical alternative is to cancel the bursts in the frequency domain, which is the subject of section 3.

## 3.0 FREQUENCY-DOMAIN SIDELOBE CANCELLATION EXPERIMENTS

Figure 3 shows the frequency-domain sidelobe cancellation configuration. The real-time sidelobe canceller was integrated with the frequency domain processor. An FFT is computed on contiguous blocks of data in both the primary and auxiliary channel. The FFT block size can range from 64 points to 16K points. All the experiments described in this paper use an FFT block size of 8K where a Hanning window

has been applied before taking the transform. For the 2.048 MHz complex sampling rate, each bin of the FFT corresponds to a subband of 250 Hz. A fixed number (128 in the present experiments) of FFT blocks are collected as the rows of a corner turning memory. The sidelobe cancellation is then performed independently on the columns of this memory. This effectively increases the number of degrees of freedom to 8K.

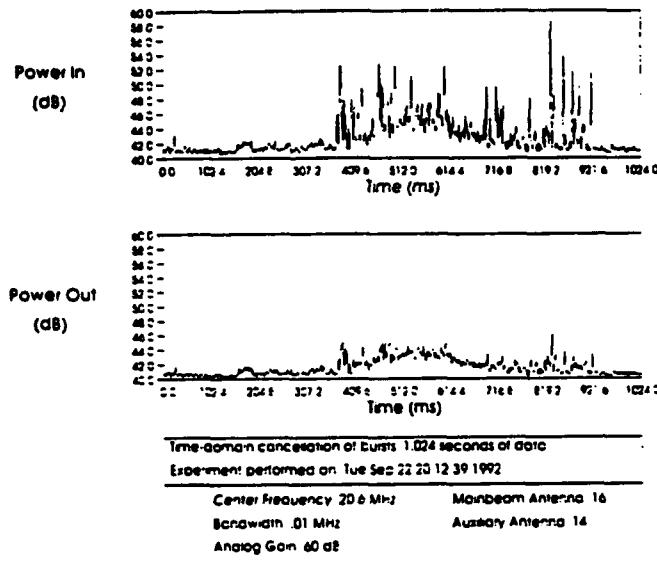


Figure 2. Time-Domain Cancellation of Noise Bursts; 10 kHz Band; 1.024 Seconds

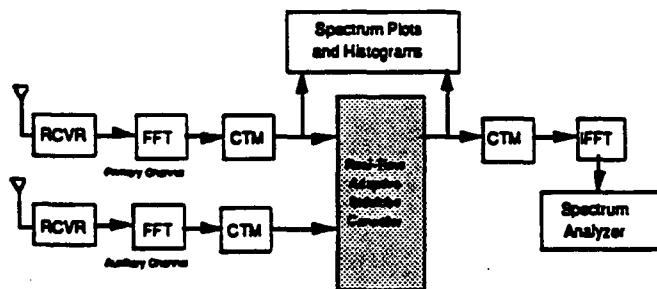


Figure 3. Frequency-Domain Sidelobe Cancellation Configuration

A periodogram of the power spectrum for the primary channel calculated using the 128 FFT blocks contained in the corner turning memory is displayed before and after the sidelobe cancellation. A user specified number of subbands

are also combined to form a single display point. When this integration factor is set at 32 (its minimum value in the current implementation), the periodogram contains 256 points each corresponding to a subband of size 8 kHz. It takes 0.512 seconds to collect the data involved in each of these periodogram plots. A second inverse FFT followed by a digital-to-analog converter can be used to display the output spectrum with an analog spectrum analyzer.

We first illustrate the cancellation of narrow-bandwidth interference. The frequency-domain subbanding approach provides effective cancellation even in bands containing significant amounts of narrow-bandwidth interference. We then focus on the ability of frequency-domain spatial filtering to remove bursts and reduce the variability of the background noise. As before, the southwest array was used in all experiments.

### 3.1 CANCELLATION OF NARROW-BANDWIDTH INTERFERENCE

Figure 4 shows a typical narrow-bandwidth interference experiment result. The digital radios were tuned to a center frequency of 15.5 MHz with a bandwidth of 1 MHz. Antennas 7 and 8 were selected as the primary and auxiliary elements, respectively. The data was collected on 30 October 1992 at 12:53 p.m. (EDT). The "power-in" periodogram corresponds to 10 sweeps involving 5.12 seconds of data. The 1 MHz band produced by the digital radios was centered in the 2.048 MHz window. The gradations on the frequency axis correspond to 204.8 kHz. A moderate number of narrow-bandwidth interferers are visible in figure 4 with interference-to-noise ratios as high as 50 dB.

The periodogram of the residual output shows a reduction of the narrow-bandwidth interferers by amounts ranging up to 40 dB. Some of the larger interferers have not been driven completely down to the noise floor. Such incomplete narrow-bandwidth interference cancellation has been observed before (Games, et al., 1991) and could be due to a number of factors. First, the 250 Hz subbands obtained from the 8K FFT could contain more than one narrow-bandwidth interferer. A second possibility could be the leakage between FFT bins. Leakage becomes particularly problematic in dense interference environments since a single FFT bin can easily contain energy corresponding to a number of different interferers arriving at different spatial directions. In the present experiment the single degree of freedom is insufficient to combat these problems, suggesting the need

for more auxiliaries. In the final analysis, however, since frequency-domain excision has been found to be an effective means of eliminating narrow-bandwidth interferers, our primary interest is in assessing the ability of a spatial filter to remove wide-bandwidth interference.

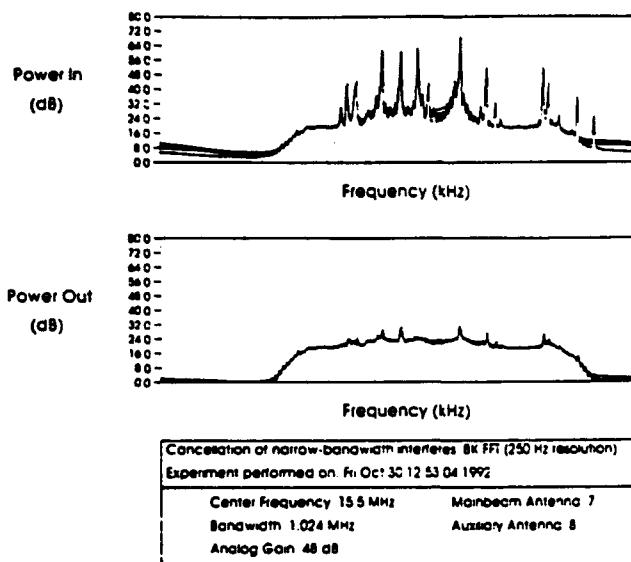


Figure 4. Frequency-Domain Cancellation of Narrow-Bandwidth Interference

### 3.2 CANCELLATION OF LONG NOISE BURSTS

As was discussed in section 2.1, bursts of wide-bandwidth noise of lengths ranging from tens of milliseconds to 1 second are common in the data collected at the MITRE-Bedford facility. Such bursts, depending on their power, could significantly increase the power level of the noise floor of multiple contiguous FFT blocks involved in the subbanded sidelobe cancellation system. Such effects were commonly observed in the 0.512 second periodograms displayed by the real-time sidelobe canceller.

The results that are described in this section were collected on 3 December 1992 when there was a low pressure center moving through New England. Coincidentally, a noticeable increase in burst activity was noted in the 5-7 MHz band on this day, suggesting a possible atmospheric connection. Figure 5 shows a typical result containing elevated FFT noise floors resulting from powerful noise bursts. The digital radios were tuned to a center frequency of

5.0 MHz with a bandwidth of 1 MHz. Antennas 12 and 11 were selected as the primary and auxiliary elements, respectively. The data was collected 9:56 a.m. (EST). The power-in display corresponds to 10 periodograms involving 5.12 seconds of data. The nominal noise floor in both the power-in and power-out plots is approximately 25 dB. Four of the periodograms displayed have markedly increased noise floors with the most powerful case corresponding to approximately 42 dB. The power-out periodograms show reductions in these elevated levels to about 28 dB, corresponding to a cancellation ratio of about 14 dB. Cancellation ratios as high as 20 dB were observed in other files.

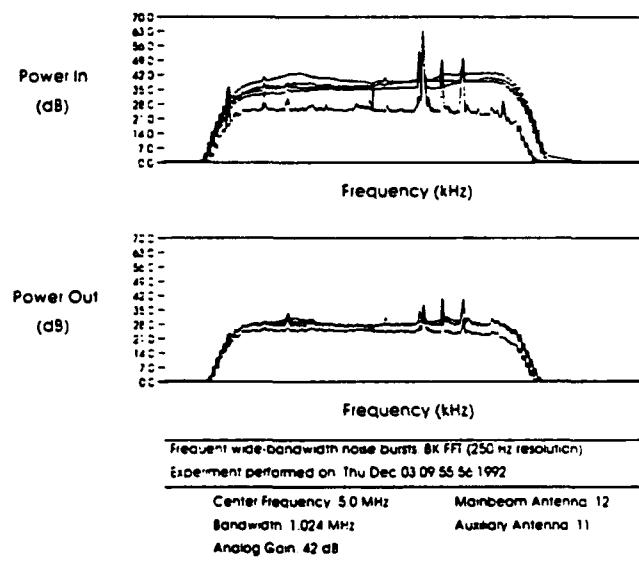


Figure 5. Frequency-Domain Cancellation of Noise Bursts; 1 MHz Band; 5.12 Seconds

To get an idea of the density of the bursts over a longer term, a five minute experiment was conducted for this same scenario beginning at approximately 10:00 a.m. (EST). Figure 6 shows the frequency-domain power display obtained. The figure indicates that there were a considerable number of bursts over the five minute period, and that the sidelobe canceller with a single degree of freedom significantly attenuated them. The power-in periodograms show a noise floor spread of approximately 20 dB in the center of the band, while the spread in the power-out periodograms has been reduced by 15 dB to about 5 dB.

#### 4.0 CONCLUSION

In conclusion, we have shown that spatial filtering can effectively eliminate burst noise at HF and that the high performance processing required for wide bandwidths can be implemented using general purpose programmable DSP chips. In the process, a scalable, reconfigurable, programmable parallel processor has been produced that is well matched to implement the variety of matrix algorithms often found in high-performance front-end signal processing (Rorabaugh, et al., 1991).

#### ACKNOWLEDGMENTS

Thanks to Dr. Stephen A. Townes and Charles J. Beanland for their helpful discussions concerning the HF band. This work was supported by the U.S. Air Force Electronic Systems Center Contract F19628-89-C-0001.

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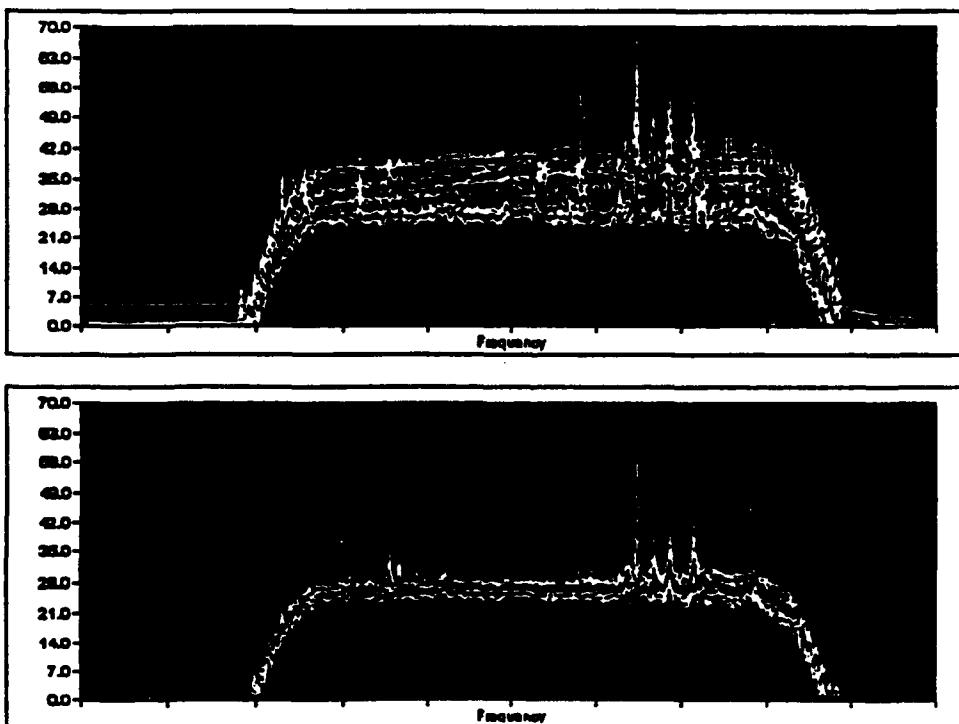


Figure 6. Frequency-Domain Cancellation of Noise Bursts; 1 MHz Band; Five-Minute Run



# A Principal Components Sidelobe Cancellation Algorithm

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**Abstract.** Previously, a so-called excess degrees-of-freedom problem associated with sidelobe cancellers whose adaptive weights are selected using conventional least squares minimization methods was identified. This problem is manifested by rising sidelobe levels and falling output signal-to-interference-plus-noise ratios as the number of degrees of freedom surpasses the number of interferers. In this paper we describe how principal components analysis methods can be used to resolve the ill effects of processing with excess degrees of freedom. Simulation results are presented which compare the performance of conventional least-squares and principal components based techniques.

## I. Introduction

Adaptive sidelobe cancellation methods are widely used in array processing applications to suppress interference and noise. These adaptive systems are composed of a primary element whose measurements consist of signal samples corrupted by noise and interference, along with a set of  $L$  auxiliary-array elements that receive only interference and noise<sup>1</sup>. The primary element may correspond to either a single sensor having high gain in the direction of the desired signal or a weighted combination of samples from a set of sensors with the weights again selected to steer the mainbeam of the array in the direction of the desired signal. The output samples of the auxiliary-array elements are adaptively weighted and summed. The difference between the primary-element samples and the weighted sum of the auxiliary data samples is then taken to form the output or residual of the sidelobe canceller. A variety of criteria exist for selecting the auxiliary-array weights. In this paper we require that these weights minimize the residual output power for a given block of  $N$  array snapshot vectors. This criteria is essentially identical to that proposed by Frost [8].

In recent years a number of authors have observed what has come to be called an excess degrees-of-freedom problem associated with adaptive-array processing algorithms [2, 3, 4, 5, 12, 14]. They have noted that as the number of degrees of freedom (i.e., the number of auxiliary-array elements,  $L$ , less

the number of constraints applied to the adaptive weights,  $K$ ) exceeds the number of interferers received by the array, both a rise in array beampattern sidelobe level and a fall in output signal-to-interference-plus-noise ratio (SINR) may be encountered as the number of adaptive sensors is increased. As shown here and elsewhere (see for example [3]), the degradation in performance due to excess degrees of freedom is dependent upon desired signal strength and may not occur if the signal is weak.

An iterated least-squares approach has been proposed [5, 14] to optimize SINR in the excess degrees-of-freedom region. This method iteratively computes the output residuals for all auxiliary array sizes ranging from 1 to  $L$ . This procedure allows the operator to select the optimal auxiliary array size by comparing the residual output powers. One method for optimizing SINR is to track the residual output power as the number of auxiliary-array elements is increased. Initially, large drops in output power will be observed until the number of degrees of freedom matches the number of interferers. When excess degrees of freedom exist, relatively small drops in residual output power will be realized resulting in an apparent plateau. If the auxiliary array size associated with the start of the plateau is selected as a stopping point for the iterated least-squares algorithm then the number of degrees of freedom will match the number of interferers. Unfortunately, while this approach may mitigate the deleterious effects of operating with excess degrees of freedom, in general it does not optimize SINR [3].

In this paper we discuss an alternative approach based upon principal components analysis that addresses the excess degrees-of-freedom problem. Improved performance is achieved by processing with a reduced-rank estimate of the data matrix formed from the auxiliary-sensor samples. This approach is based upon the work of Eckart and Young [1] and has been used extensively in spectral estimation to improve the accuracy of various AR modeling techniques (see [9, 10]). Simulation results suggest that this technique prevents SINR loss when there is an excess degrees-of-freedom problem. It also allows for better control of the adapted beampattern, thus avoiding the rise in average sidelobe level encountered by least-squares processors operating in the excess degrees-of-freedom region.

<sup>1</sup>In general, the auxiliary-array elements also receive the signal. However, the signal is often sufficiently weak that it can be ignored. When strong signals exist constraints may be applied to effectively remove the signal component from the auxiliary-array elements.

## II. The Conventional Least-Squares Sidelobe Canceller

Figure 1 depicts the adaptive sidelobe canceller configuration used in this paper. We let  $\mathbf{x}$  denote a length  $N$  vector containing the primary element samples. If we let  $y_{ij}$  denote the  $i$ -th sample measured by the  $j$ -th auxiliary array element, then the auxiliary array data matrix has the form

$$\mathbf{Y} = \begin{bmatrix} y_{11} & y_{12} & y_{13} & \cdots & y_{1L} \\ y_{21} & y_{22} & y_{23} & \cdots & y_{2L} \\ \vdots & & & & \\ y_{N1} & y_{N2} & y_{N3} & \cdots & y_{NL} \end{bmatrix}.$$

We assume that the sensor measurements are composed of a far-field signal having known direction,  $D$  far-field interferers, and spatially-white noise having uniform variance across the array. Finally, we let  $\mathbf{w}$  denote an  $L \times 1$  vector of adaptive weights  $\mathbf{w} = [w_1, w_2, \dots, w_L]^T$ . The adaptive weights are selected to solve the following least-squares problem:

$$\min_{\mathbf{w}} \|\mathbf{x} - \mathbf{Yw}\|_2^2.$$

The form of the weight vector which solves this problem is well known [6] and has the form

$$\mathbf{w} = (\mathbf{Y}^H \mathbf{Y})^{-1} \mathbf{Y}^H \mathbf{x}.$$

The residual output has the form  $\mathbf{z}_{ls} = \mathbf{x} - \mathbf{P}_Y \mathbf{x}$  where  $\mathbf{P}_Y$  is an orthogonal projection matrix which projects  $\mathbf{x}$  onto the column space of  $\mathbf{Y}$ .

The approach outlined above is a useful technique for suppressing plane-wave interference provided the auxiliary array element measurements do not contain a signal component. This requirement is essentially satisfied when the desired signal is weak relative to the background noise. However, when a significant signal component in the auxiliary channels exists, suppression of the desired signal may result. In order to avoid cancelling strong signals, constraints can be applied to the adaptive weights to prevent the weighted sum of the auxiliary-array sensor samples from containing

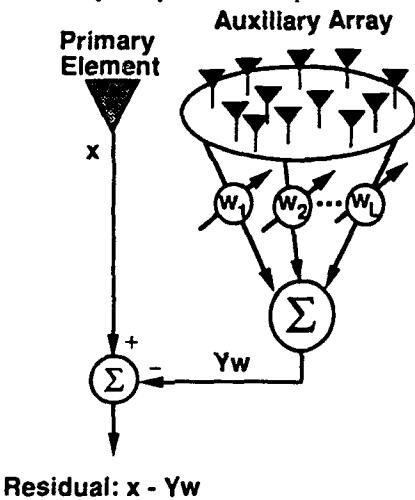


Figure 1. Sidelobe Canceller Array Configuration

desired-signal components. This is achieved by requiring that the auxiliary-array weight vector be orthogonal to the direction vector of the desired signal (denoted by  $\mathbf{a}(\theta_0, \phi_0)^*$ , where  $*$  represents the complex conjugate operator). We require then that

$$\mathbf{a}(\theta_0, \phi_0)^H \mathbf{w} = 0. \quad (1)$$

Other constraints including multiple point and derivative constraints can also be applied in order to reduce sidelobe canceller sensitivity to knowledge of the signal bearing. We assume  $K$  linear constraints of the form:

$$\mathbf{C}^H \mathbf{w} = \mathbf{f}$$

have been applied, where  $\mathbf{C}$  denotes the  $K \times L$  constraint matrix and  $\mathbf{f}$  is a  $K \times 1$  response vector. It is sufficient for our purposes to consider constraints for which  $\mathbf{f}$  is a  $K \times 1$  null vector, noting that the techniques discussed here can be easily extended to arbitrary response vectors.

If the Lagrange multiplier approach is used to solve the constrained least-squares problem, then we must find the weight vector which minimizes

$$\|\mathbf{x} - \mathbf{Yw}\|_2^2 - \lambda^H \mathbf{C}^H \mathbf{w}, \quad (2)$$

where  $\lambda$  is a vector containing the Lagrange multipliers. Techniques for minimizing (2) with respect to  $\mathbf{w}$  are well known [11]. When these methods are applied the residual output for the constrained least-squares sidelobe canceller takes the form:

$$\mathbf{z}_{cls} = \mathbf{x} - \mathbf{P}_Y \mathbf{x} + \mathbf{P}_C \mathbf{x}$$

for  $\mathbf{P}_C = \mathbf{B}(\mathbf{B}^H \mathbf{B})^{-1} \mathbf{B}^H$  where  $\mathbf{B} = \mathbf{Y}(\mathbf{Y}^H \mathbf{Y})^{-1} \mathbf{C}$ , and  $\mathbf{P}_Y$  defined earlier.

The block processing schemes just described provide useful means for suppressing plane-wave interference measured by an array. However, these techniques do suffer from a so-called excess degrees-of-freedom problem as outlined in [2, 3, 4, 5, 14]. Consider, for example, figures 2 and 3 which depict the unadapted beampattern for the primary element and the adapted beampattern obtained using eight auxiliary-array elements. The primary element samples were obtained by weighted sum of the outputs for all sixteen array elements using a 30 dB Dolph-Chebyshev taper. The array used to form the primary element was linear with 16 sensors uniformly spaced one-half wavelength apart. In this case, two interferers having SNRs of 40 dB and bearings of 20° and 40° impinge upon the array. A desired signal arrives at 0° with SNR of 0 dB. The auxiliary-array elements form a linear array with one-half wavelength spacing. Note the rise in sidelobe level associated with the adapted pattern. Computer simulations have also been used to demonstrate the deterioration in SINR as the auxiliary array size increases beyond the size necessary to cancel the interferers. In the next section we present a procedure based upon principal components analysis that produces beampatterns that closely replicate the quiescent pattern of the primary

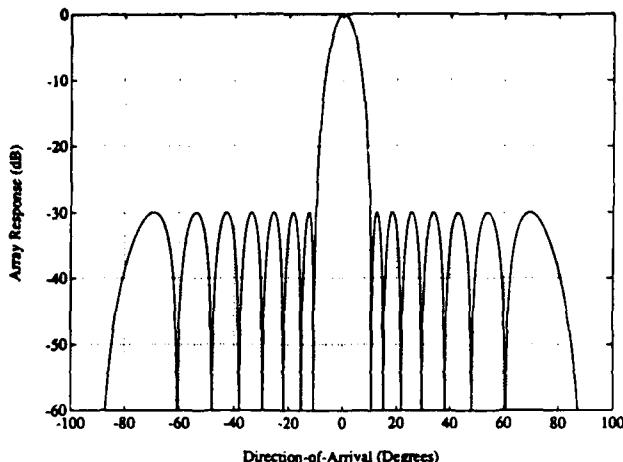


Figure 2. Beampattern for a 16 Element Linear Array with -30 dB Dolph-Chebyshev Weights

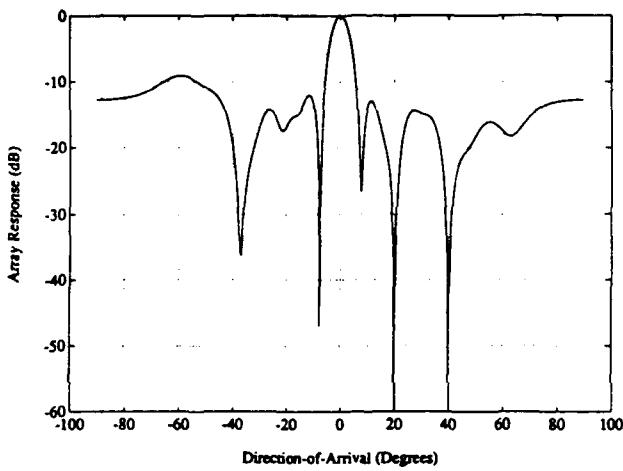


Figure 3. Adapted (Least-Squares) Beampattern Using 8 Auxiliary-Array Elements

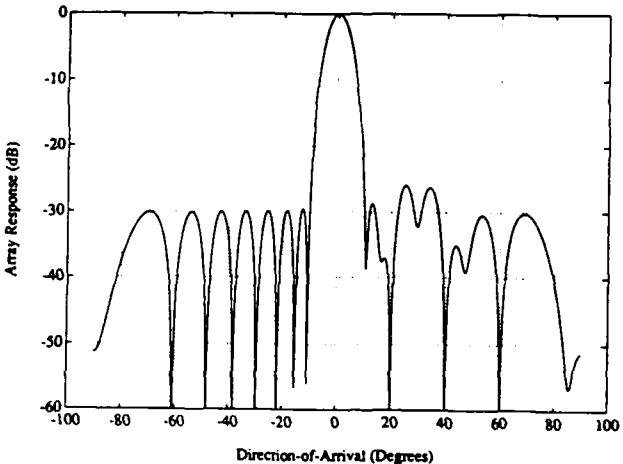


Figure 4. Adapted (Principal Components) Beampattern Using 8 Auxiliary-Array Elements and 3 Principal Components

element and that generally provide improved SINR performance. For comparison, we show the beampattern obtained using the principal components algorithm in figure 4. Note the close agreement between the unadapted pattern (figure 2) and the results shown for the principal components based sidelobe cancellation algorithm.

### III. The Principal Components Algorithm

In this section we outline a technique based upon a theorem of Eckart and Young [1] that effectively eliminates the ill effects of processing with excess degrees of freedom. The principal components method reduces the background noise contained in the auxiliary-data matrix  $\mathbf{Y}$  by forming a reduced-rank estimate of  $\mathbf{Y}$  using a theorem outline in [1]. The use of principal components analysis not only has the desired effect of removing noise but also of controlling the number of degrees of freedom available for processing the primary-element samples. The technique outlined here has been used extensively in time series analysis to obtain improved estimates of the frequency spectra of autoregressive processes (see, for example [9]). In this paper, we demonstrate how it can be applied in array processing to resolve the excess degrees-of-freedom problem.

In the sequel we make use of the singular value decomposition (SVD) of the auxiliary array data matrix  $\mathbf{Y}$ . The SVD of this matrix can be written as

$$\mathbf{Y} = \mathbf{U}\Sigma\mathbf{V}^H,$$

where  $\mathbf{U}$  and  $\mathbf{V}$  are  $N \times N$  and  $L \times L$  unitary matrices and  $\Sigma$  is  $N \times L$  and has the form

$$\Sigma = [\text{diag}(\sigma_1, \sigma_2, \dots, \sigma_L) \mid \mathbf{0}]^T.$$

The nonzero elements of  $\Sigma$  correspond to the singular values of  $\mathbf{Y}$ , while the columns of  $\mathbf{U}$  and  $\mathbf{V}$  represent the left and right singular vectors of this matrix. In the subsequent development we assume without loss of generality that  $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_L > 0$ .

Eckart and Young have shown that the rank  $M$  matrix ( $M < N, L$ ) which best approximates an  $N \times L$  matrix  $\mathbf{Y}$  is given by

$$\mathbf{Y}_M = \mathbf{U}_M \Sigma_M \mathbf{V}_M^H,$$

where  $\mathbf{U}_M$  and  $\mathbf{V}_M$  are  $N \times M$  and  $L \times M$  matrices containing the first  $M$  columns of  $\mathbf{U}$  and  $\mathbf{V}$ , respectively. The matrix  $\Sigma_M$  has the form  $\Sigma_M = \text{diag}[\sigma_1, \dots, \sigma_M]$ .

The unconstrained principal components method presented here first obtains the best rank  $D + 1$  approximation to  $\mathbf{Y}$ , where  $D + 1$  denotes the total number of interferers and signals. Subsequently, the least-squares problem

$$\min_{\mathbf{w}} \|\mathbf{x} - \mathbf{Y}_{D+1}\mathbf{w}\|_2^2$$

is solved resulting in a residual,  $\mathbf{z}_{pc}$ , of the form

$$\mathbf{z}_{pc} = \mathbf{x} - \mathbf{U}_{D+1}\mathbf{U}_{D+1}^H\mathbf{y},$$

where  $\mathbf{U}_{D+1}\mathbf{U}_{D+1}^H$  is an orthogonal projection matrix which

projects  $\mathbf{x}$  onto the column space of  $\mathbf{Y}_{D+1}$ . We select the reduced rank to be  $D+1$  since this value provides the sidelobe canceller with the minimum number of degrees of freedom necessary for cancelling the interferers. We note that  $D$  can be determined from the singular values of  $\mathbf{Y}$  using, for example, methods outlined in [13].

Constrained versions of the principal components algorithm have also been developed. One approach to applying constraints is to simply approximate the projection matrix  $\mathbf{P}_c$  as

$$(\mathbf{P}_c)_M = \mathbf{B}_M (\mathbf{B}_M^H \mathbf{B}_M)^{-1} \mathbf{B}_M^H$$

where

$$\mathbf{B}_M = \mathbf{Y}_M (\mathbf{Y}_M^H \mathbf{Y}_M)^+ \mathbf{C},$$

$+$  denotes the pseudo-inverse and  $M$  is selected to be  $D+K$ . The residual output then takes the form

$$\mathbf{z}_{\text{cp}} = \mathbf{x} - \mathbf{U}_M \mathbf{U}_M^H \mathbf{x} + (\mathbf{P}_c)_M \mathbf{x}.$$

A drawback of this approach is that the solution corresponds to a weight vector that satisfies a projected version of the constraints. That is, the resulting weight vector satisfies the constraint  $\mathbf{C}^H \mathbf{V}_M \mathbf{V}_M^H \mathbf{w} = \mathbf{0}$ . The desired constraints will be exactly met whenever the columns of  $\mathbf{C}$  lie in the column space of  $\mathbf{V}_M$ . Simulation results suggest that when  $\mathbf{C}$  corresponds to the steering vector of the signal as in (1), the desired constraint will be closely satisfied. We can insure that the constraints are exactly met by using a blocking matrix to first apply the constraints (see Griffiths and Jim [7]) and by then obtaining a reduced rank estimate of the transformed auxiliary array data matrix. To obtain the blocking matrix we first perform a QR decomposition on  $\mathbf{C}$  [6]:

$$\mathbf{C} = [\mathbf{Q}_1, \mathbf{Q}_2] \begin{bmatrix} \mathbf{R} \\ \mathbf{0} \end{bmatrix}$$

where  $\mathbf{R}$  is a  $K \times K$  upper triangular matrix,  $\mathbf{Q}_1$  is  $L \times K$  and  $\mathbf{Q}_2$  is a  $L \times (L-K)$  matrix whose columns span the orthogonal complement of the column space of  $\mathbf{C}$ . Then the minimized residual for the constrained least-squares problem is equivalent to the residual obtained by solving the unconstrained problem (see [6]):

$$\min_{\mathbf{u}} \|\mathbf{x} - \mathbf{Y} \mathbf{Q}_2 \mathbf{u}\|_2^2.$$

The principal components algorithm can be implemented by replacing  $\mathbf{Y} \mathbf{Q}_2$  with its rank  $D$  estimate and subsequently solving for the minimized output residual. The constraints are satisfied since they are applied before the rank reduction is performed. The advantage, however, of the approach outlined earlier is that when processing multiple mainbeam directions only a single SVD is necessary; the latter procedure requires multiple SVDs.

As our simulation results will show the principal components algorithm presented here provides a useful solution to the excess degrees-of-freedom problem. Moreover, it gen-

erally provides performance superior to that of the iterated least-square algorithm by allowing for the optimal selection of the number of degrees of freedom while also enabling the sidelobe canceller to achieve complete cancellation of the interference [3].

#### IV. Simulation Results

In this section we compare the performance of the conventional least-squares and principal components algorithms using the results of computer simulations. The simulated array consisted of 1000 elements randomly placed over a circular aperture of 200 wavelengths in radius. Up to forty auxiliary-array elements were randomly selected from the full set of 1000. The primary-element samples were obtained by combining the outputs of all 1000 elements. The element measurements were weighted so that the main beam of the primary element was steered in the direction of the desired signal. The magnitudes of the weights were fixed at .001. The average sidelobe level for this array was  $-30.0$  dB. Both the signal and interferers were modeled as narrowband Gaussian processes.

In the first set of simulation runs we compared the performance of a conventional least-squares method with that of the principal components technique outlined in section 3 using average sidelobe level as a measure. In the first set of simulations the desired signal was located at an azimuth of  $21^\circ$ , an elevation of  $26^\circ$  and had an input signal-to-noise ratio (SNR) of  $-10$  dB per element. Two interferers were also included. They had SNRs of  $40$  dB and  $50$  dB per element, azimuths of  $10^\circ$  and  $25^\circ$  and a common elevation of  $30^\circ$ . We used 10 auxiliary array elements to cancel the interferers. The number of snapshots was set at 100 and one auxiliary array constraint of the form given in equation (1) was used to prevent cancellation of the desired signal. For the first set of runs the first principal components algorithm described in section III was used with  $M$  set to 3.

Figures 5 and 6 depict elevation cuts of  $26^\circ$  and  $30^\circ$  corresponding to the locations of the signal and interferers for the least-squares (dotted line) and the principal components (solid line) algorithms. Comparing the two techniques we see that the adapted sidelobe level for the least-squares algorithm was generally higher than that achieved using principal components analysis. The average sidelobe level for the least-squares processor was  $-21.6$  dB compared to  $-28.2$  dB for the principal components method. As we see from figure 6, both techniques placed nulls in the directions of the interferers.

Figures 7 and 8 demonstrate the beampatterns obtained when the strength of the signal in the above scenario is reduced to  $-40$  dB per element. From these results we see that average sidelobe levels for the two techniques were nearly identical. This observation suggests that for weak signals no benefit was derived from using the principal components technique since no excess degrees-of-freedom problem existed. We should note that when residual clutter or interference exists in the mainlobe, high sidelobes may result even though the desired signal is weak.

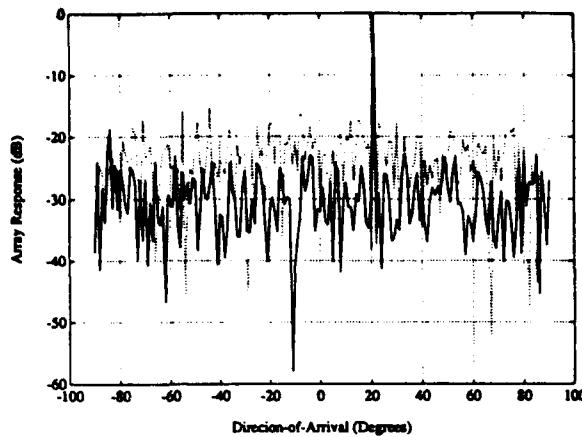


Figure 5. Conventional Least-Squares (Dotted Line) vs. Principal Components (Solid Line) for a -10 dB Signal; 26° Elevation Cut

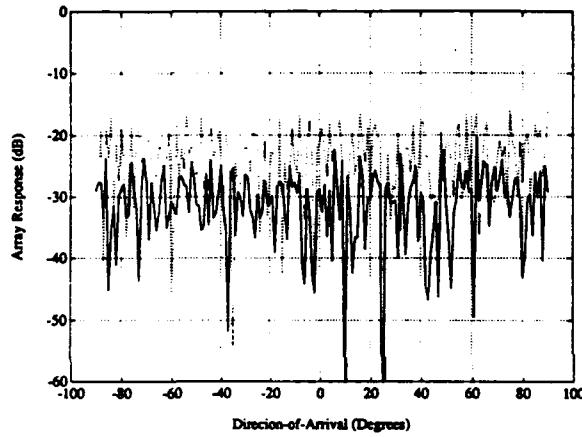


Figure 6. Conventional Least-Squares (Dotted Line) vs. Principal Components (Solid Line) for a -10 dB Signal; 30° Elevation Cut

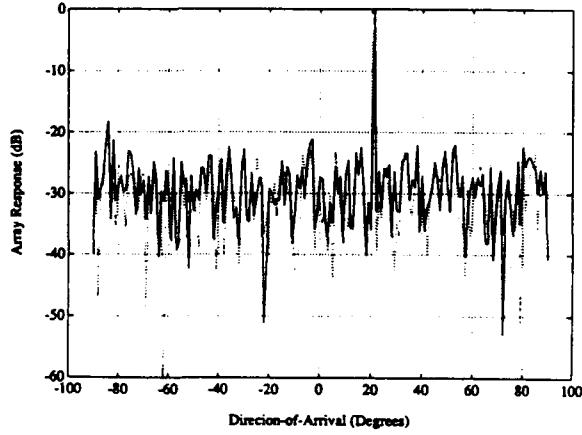


Figure 7. Conventional Least-Squares (Dotted Line) vs. Principal Components (Solid Line) for a -40 dB Signal; 26° Elevation Cut

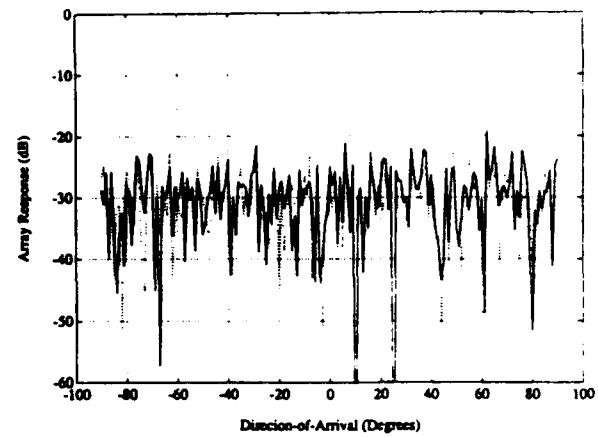


Figure 8. Conventional Least-Squares (Dotted Line) vs. Principal Components (Solid Line) for a -40 dB Signal; 30° Elevation Cut

A comparison of signal-to-interference-plus-noise ratio (SINR) achieved using both the principal components and least-squares procedures was also conducted. The planar array and signal scenario described above was again run with the power of the desired signal set at -20 dB per element and the number of auxiliaries set at 40. Figure 9 depicts the results obtained for both the iterated least-squares and the principal components methods averaged over 100 trials. In this set of runs we used the blocking matrix based principal components algorithm with a single constraint. The number of principal components was selected to be 2. Note the superior performance of the principal components method compared to that achieved using the iterated least-squares procedure. It is also interesting to note the fall in SINR for the least-squares processor as the number of auxiliary array elements exceeds 10. We attribute this fall to signal cancellation associated with excess degrees of freedom (see [3]).

When the identical scenario was run with the signal SNR set to -40 dB the conventional least-squares technique outperformed its principal components based counterpart as shown in figure 10. Note that for this example there appears to be no deterioration in the performance of the iterated least-squares approach due to excess degrees of freedom. As with average sidelobe level, a substantial improvement in performance is achieved by using principal components analysis when the signal is strong; however, at lower SNRs the performance of the least-squares algorithm is superior due to its ability to further suppress background noise. Analysis reported in [3], shows that for this example the dividing line between weak and strong signals occurs at -30 dB. Of course, for different array configurations or primary element tapers this value will fluctuate. If, for example, the number of sensors used to form the primary element is increased to 10,000 the cut-off falls to -40 dB when a uniform weighting scheme is used.

## V. Conclusion

In this paper we applied principal components analysis techniques to an adaptive sidelobe canceller and demonstrated the ability of this procedure to resolve problems asso-

ciated with processing with excess degrees of freedom. The principal components based sidelobe canceller uses methods well known in the spectral estimation literature to properly constrain the degrees of freedom available for processing. As our simulation results suggest, the principal components algorithm achieves a lower average sidelobe level and a higher output SINR than its conventional least-squares counterpart, provided the desired signal is relatively strong. For weak signals, however, there appears to be no particular advantage to using the principal components method since processing with excess degrees of freedom does not appear to be a problem. We note, however, that if strong mainlobe interference exists a serious degradation in sidelobe level may result due to excess degrees of freedom even though the signal is weak. The price paid for the benefits of principal components processing includes an increase in computational complexity due to the singular value decomposition necessary for obtaining a reduced rank estimate of the desired signal.

#### Acknowledgment

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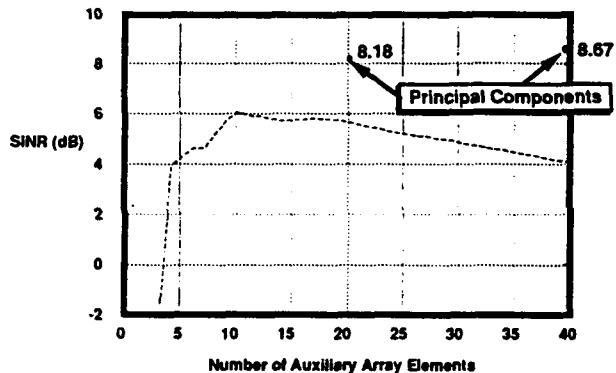


Figure 9. SINR vs. Auxiliary Array Size for the Conventional Least-Squares and Principal Components Algorithms with a -20 dB Signal

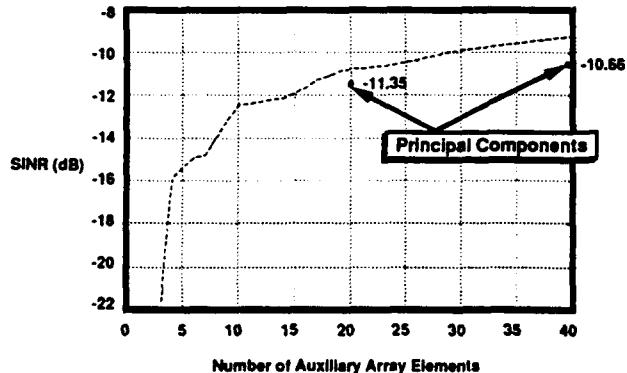


Figure 10. SINR vs. Auxiliary Array Size for the Conventional Least-Squares and Principal Components Algorithms with a -40 dB Signal

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